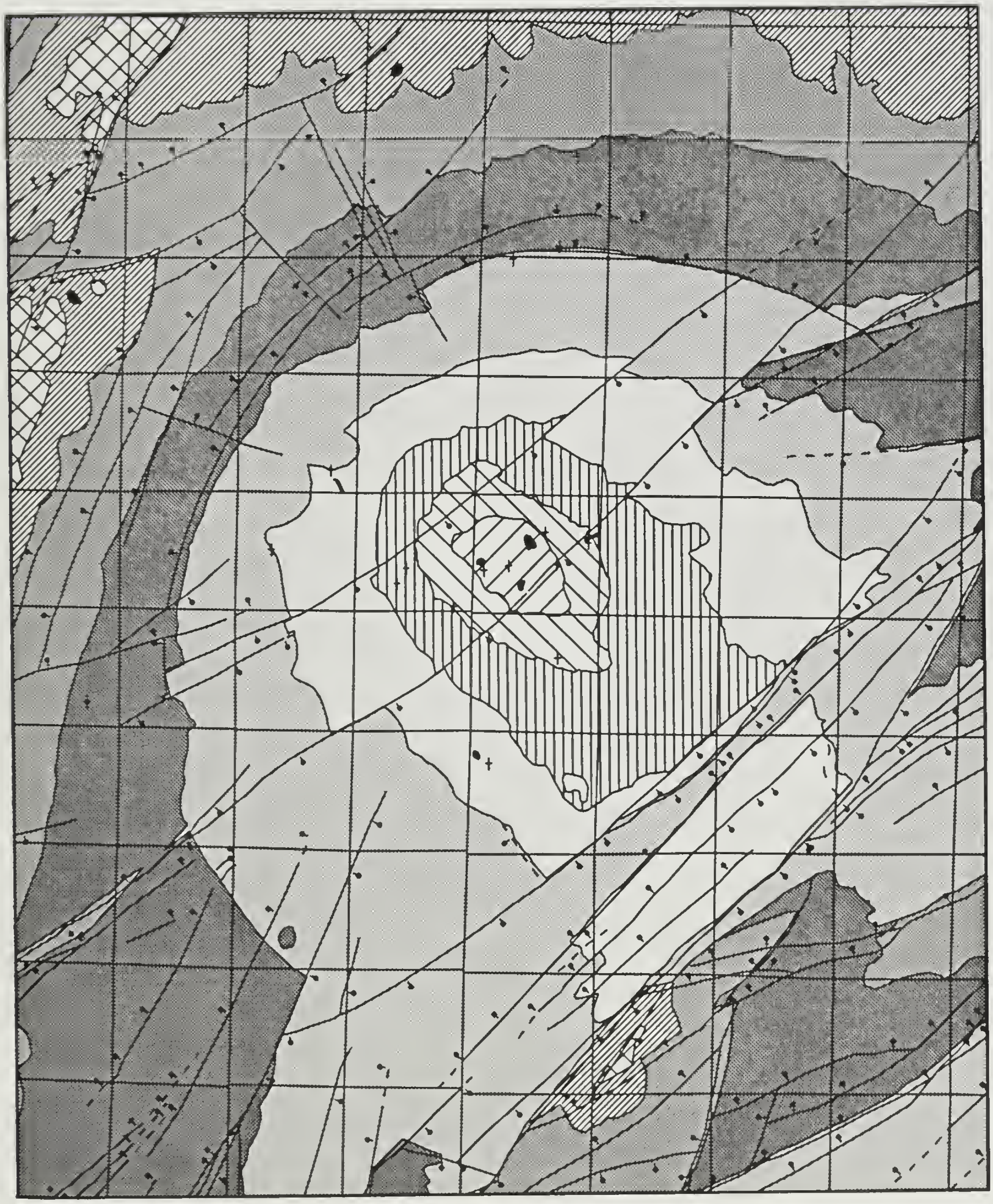
INTRUSIVE BRECCIAS AT HICKS DOME

Hardin County, Illinois

J. C. Bradbury and J. W. Baxter



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ILLINOIS STATE GEOLOGICAL SURVEY

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Conversations with many investigators have added to our understanding of the processes that combined to form the enigmatic structure known as Hicks Dome. We are grateful for the critical review of the manuscript by several colleagues at the Ilinois State Geological Survey, J. James Eidel, Jonathan H. Goodwin, Richard D. Harvey, and Randall E. Hughes. Careful review and suggestions by Timothy Hayes, U. S. Geological Survey, were especially helpful.

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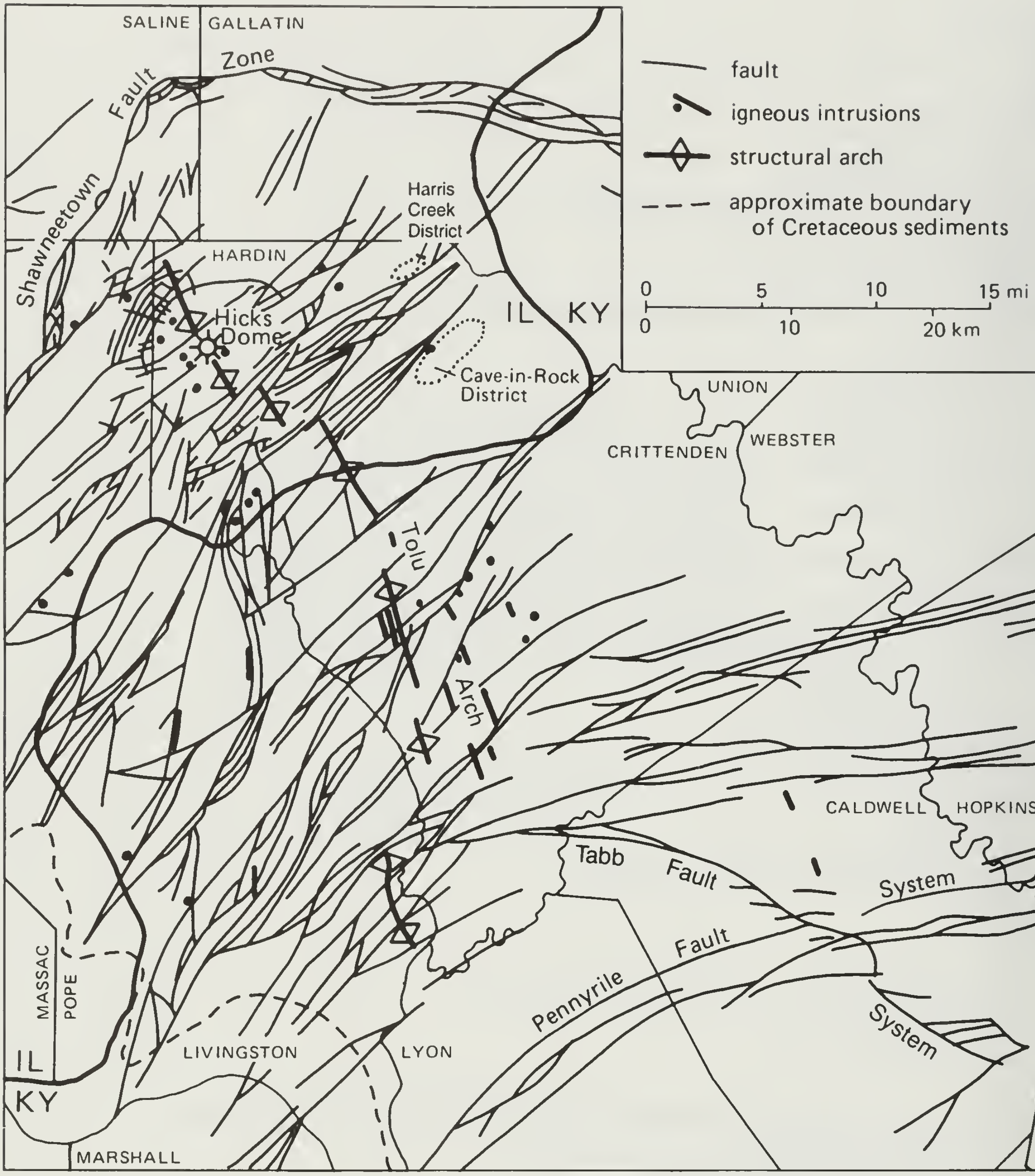


Figure 1 Major structural features and igneous intrusive rocks, Illinois-Kentucky Fluorspar District (modified from Nelson 1991, p. 236).

ABSTRACT

Within a 1- by 2-mile oval of Devonian and Lower Mississippian exposures at Hicks Dome are several occurrences of rocks, including intrusive breccia and one ultramafic dike, genetically related to alkalic magmatic activity. Additional breccias of less clear igneous affinities are more numerous.

The breccias at Hicks Dome are exposed as dikes and other bodies of indeterminate shape in a central area, and chiefly as dikes in the dome's surrounding New Albany shale and Fort Payne Formation outcrop belts. The breccia dikes exhibit a crudely radial arrangement around the dome, but most have strikes that fall within the major regional fracture trends.

Breccias are divided on the basis of geometry and composition into three types: shatter, vent, and carbonatitic. *Shatter breccias*, composed of fragments of the immediate wall rock, are commonly tabular, essentially vertical bodies. *Vent breccias* occur in bodies of irregular or indeterminate form and exhibit evidence of a large amount of vertical displacement of some included fragments. Many shatter and vent breccias are intensely silicified. Four breccia exposures and a core intersection have both igneous and sedimentary rock fragments in a matrix of carbonate minerals that we believe were deposited from a CO_2-rich gas exsolved from an alkaline magma at depth; these breccias are classified as *carbonatitic* after Gold (1972).

Mineralization is largely confined to the central area of the dome and includes fluorite, barite, sphalerite, and galena (most common and confined within breccias); bertrandite (beryllium silicate) in two breccia bodies; and brockite (calcium thorium yttrium phosphate) and florencite (cerium aluminum phosphate) in a third breccia. Abnormal amounts of thorium, rare earths, and niobium were measured in breccia cuttings from a test well near the center of the dome. Vent and carbonatitic breccias probably resulted from explosive release of gases heated by or derived from an alkalic magma at depth.

The ages of the breccia intrusion and mineralization episodes are unknown, but they probably are in the interval from early Permian to early Late Cretaceous.

INTRODUCTION

Purpose and Scope of Study

Discovery of mineralized, radioactive breccia in an oil test hole (the Hamp well) near the center of Hicks Dome (Brown et al. 1954) and subsequent exploration for radioactive minerals focused attention on this structure in southern Illinois (Bradbury et al. 1955, Trace 1960). The possible economic significance of Hicks Dome mineralization and the relationship of igneous activity at Hicks Dome to the deposition of fluorspar-lead-zinc-barite ore bodies of the Illinois-Kentucky Fluorspar District have been of special interest. Field investigations by the Illinois State Geological Survey revealed numerous additional occurrences of breccia, mostly as dikes around the periphery of the central area of the dome. This report discusses the occurrence of the known breccias and their petrography, chemical composition, mineralization, and origin. The data and interpretation presented should add to the understanding of this enigmatic domal structure.

Location and Setting

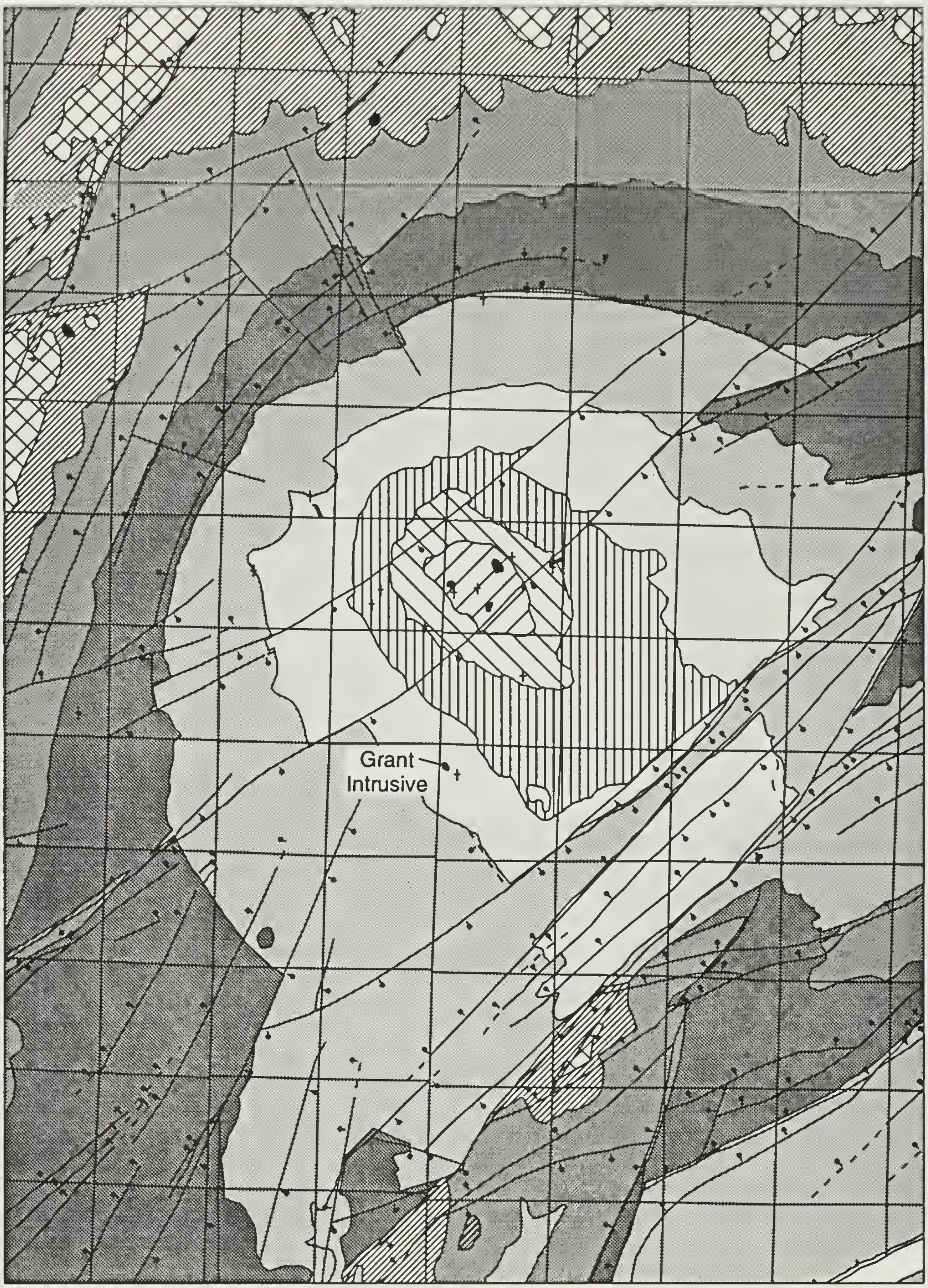
Hicks Dome is both a structural and topographic high situated in Hardin County, Illinois, in the northwestern part of the Illinois-Kentucky Fluorspar District (fig. 1). Structurally, the area of Hicks Dome extends several miles from its center. Radial and concentric (ring) faults that have been mapped in Mississippian strata approximately 3 miles (5 km) downdip from the apex attest to the dome's formation by upward forces. The dome has a central area where Devonian and Lower Mississippian sedimentary rocks are at the surface (fig. 2). The central area is oval and approximately 1 by 2 miles (1.6 by 3.2 km); its long dimension is oriented northwest to southeast. Also in the oval is a central topographic high (hill), designated Hicks Dome on the Karbers Ridge Quadrangle topographic map. Unless otherwise stated, the term Hicks Dome is used in its more limited topographic sense and conforms to local usage. Hicks Dome therefore includes the central hill, the valley that encircles the hill, and the outer ridge that forms the periphery of the distinctive oval outcrop pattern. The outer ridge is nearly as high as the central hill.

Hicks Dome, in a regional sense, comprises the northwest end of the Tolu Arch, a poorly defined uplift that traverses the fluorspar district from southeast to northwest (fig. 1). A broad belt of block faulting appears to offset the axial trend of the Tolu Arch. Farther to the southeast in Kentucky, the Tolu Arch becomes difficult to trace because of block faulting, but offset segments of the axis can be identified in several of the fault blocks (fig. 1 and Trace 1976, p. 69).

Methods of Investigation

Detailed field mapping was conducted within the 1- by 2-mile (1.6- by 3.2- km) oval area at the center of Hicks Dome. As bedrock outcrops are relatively rare downdip from the escarpment, the boundary of the study area was chosen to be the top ridge of the Fort Payne Formation.

Samples were taken from all observed breccia outcrops and from clusters of boulders that collectively appeared to represent individual breccia occurrences. A previously known exposure of breccia, the Grant Intrusive located about 4,000 feet (1.2 km) south of the study area (fig. 2), was included in the study because it provided relatively unweathered samples of a breccia type encountered in the mapped area. Thin sections were



QUATERNARY SYSTEM

alluvial deposits

PENNSYLVANIAN SYSTEM

Tradewater Formation
shale, sandstone, and thin coal

Caseyville Formation

MISSISSIPPIAN SYSTEM

upper Pope Group, above top of Glen Dean Limestone

lower Pope Group, below top of Glen Dean Limestone

Ste. Genevieve-St. Louis Limestone

Salem-Ullin Limestone

Fort Payne-Springville Formation

MISSISSIPPIAN AND DEVONIAN SYSTEM

New Albany Shale Group

DEVONIAN SYSTEM

Lower And Middle Devonian Series

IGNEOUS AND BRECCIATED ROCK

breccias

+ mafic dikes

faults

Figure 2 Geologic map of Hicks Dome.

made of relatively fresh samples and studied petrographically. Badly weathered samples were gently disaggregated and studied under binocular microscope and/or by oil immersion. Fifty-seven samples were qualitatively scanned by emission spectrograph to determine the elements present and their relative abundance. Twelve of the samples were further analyzed by X-ray fluorescence for major and minor constituents and 19 samples were selected for trace element analysis by emission spectrography. Fluorine (as fluoride) analyses were carried out by fluoride ion-selective electrode. X-ray diffraction studies supplemented these methods. The geochemical data were examined to identify suites of elements intrinsic to the depositional environment of the country rocks and anomalies related to postdepositional igneous and epigenetic processes. Recognition of an anomalous suite of elements provides a method for geochemical prospecting.

REGIONAL SETTING AND STRUCTURAL HISTORY

Hicks Dome and the Tolu Arch are located at the intersection of the northeast-trending Reelfoot Rift and its east-trending extension into Kentucky, the Rough Creek Graben (fig. 3). The rift and the graben constitute the New Madrid Rift System in southern Illinois and western Kentucky. The north and northwest boundaries of this system are marked by the Rough Creek-Shawneetown Fault System and the Lusk Creek Fault Zone, respectively. The southern boundary in Kentucky, less clearly defined, is believed to partially coincide with the Pennyrile Fault System. From the intersection of the Shawneetown and Lusk Creek Fault Zones, the rift is 45 to 50 miles (70 to 80 km) wide; Hicks Dome is located about 17 miles (11 km) due east of the intersection.

The Reelfoot Rift (Ervin and McGinnis 1975) and the Rough Creek Graben (Soderberg and Keller 1981) are considered to be part of a system of "failed rifts" that developed in response to extension and related in time to the postulated Eocambrian/Cambrian breakup of a Precambrian supercontinent (Bond et al. 1984). During that early Paleozoic history, the Hicks Dome area appears to have been an aulocogen (Hoffman, Dewey, and Burke 1974). Deposition (probably in part continental) and possibly intrusion and volcanism was restricted to an axial graben (Nelson and Kolata 1991, Sargent 1991). Subsidence within the Reelfoot–Rough Creek fault zone was apparently greater than that in the adjacent platforms to the southeast, northeast, and north during later stages. Thus, the dome has apparently deformed sediments within a basin containing the thickest accumulation of Paleozoic sedimentary rocks known anywhere in the midcontinent. Near the end of the Paleozoic (late Pennsylvanian to Early Permian), the African and South American plates collided with the North American, thus plate forming the supercontinent Pangea. According to Kolata and Nelson (1991), the resultant compressional stresses caused high-angle reverse faulting along fault zones referred to as the Rough Creek–Shawneetown Fault System and the Lusk Creek Fault Zone.

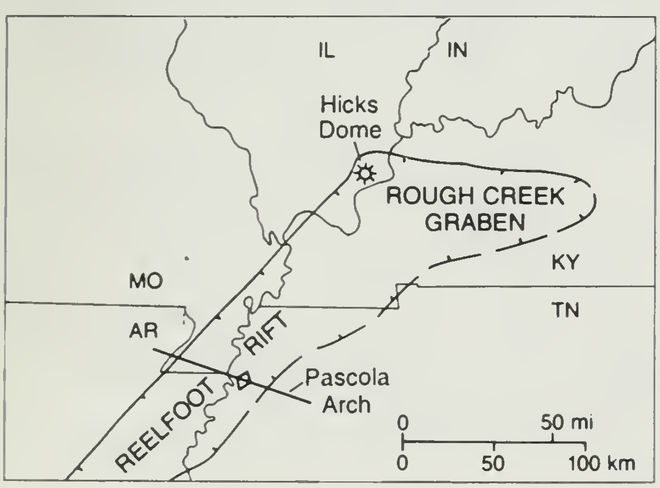
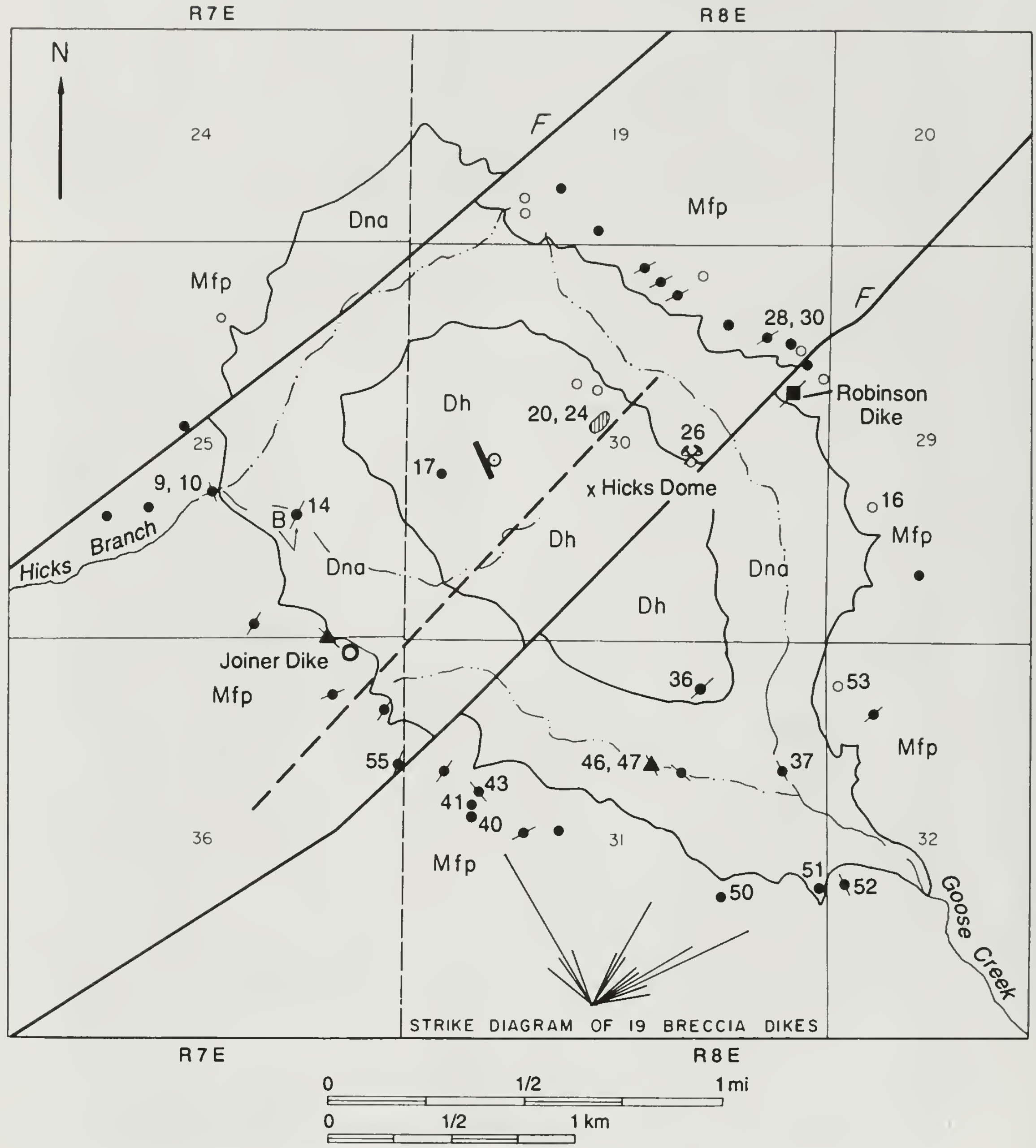


Figure 3 Relationship of Hicks Dome to Precambrian Rift Zones (modified from Heigold 1991, fig. 17-1).

The Tolu Arch (fig. 1) appears to have been uplifted at about this time and the resultant tensional fractures were intruded by a swarm of northwest-trending mafic dikes that yield concordant early Permian potassium-argon (K-Ar) and rubidium-strontium (Rb-Sr) dates (Zartman et al. 1967, Nelson and Lumm 1984). Mafic dikes in the Cottage Grove Fault System, as much as 10 miles north of the Shawneetown Fault Zone, appear to radiate slightly from the northwestward trend of the Tolu Arch. These dikes are the same age and composition as some of the mafic dikes in the fluorspar district; however, except for the early Permian mafic dikes, the age relationship of igneous and structural events related to evolution of the Reelfoot Rift, the Illinois Basin, and the Illinois–Kentucky Fluorspar District is poorly defined.

The mineralized faults of the Illinois-Kentucky Fluorspar District that trend northeast to southwest bound a series of grabens that offset the axis of the Tolu Arch (fig. 1). Individual fluorspar-district faults offset, and are therefore younger, than the northwest-trending Permian mafic dikes. This faulting occurred mostly after Early Permian and before Late Cretaceous, but evidence of minor Cretaceous movement has been cited (Rhoades and Mistler 1941, Amos 1967). Brittle and easily cleaved fluorite in major veins, however, is not generally crushed, as would be expected, by significant fault movements after the veins were formed. Those crushed-ore occurrences that have been cited as possible evidence of postmineralization movement are related to small or marginal vein deposits within the fault systems that form the northeast boundaries of major grabens.



- Vent breccia outcrop
- Breccia boulders
- Shatter breccia dike, strike indicated
- Probably same, strike not determined
- Carbonatitic breccia, strike indicated
- Lamprophyre, strike indicated
- Abandoned mine
- 9 Numbered sites indicate sample localities for chemical analyses (see table 3), thin sections and/or typical outcrops (plate 1).
- Exploration trench
- Core 11IL
- Hamp well
- B Bertrandite occurrence
- F Fault
- Mfp Fort Payne Formation and younger
- Dna Devonian New Albany Shale
- Dh Devonian Chert and Limestone

Figure 4 Breccia occurrences at Hicks Dome, Hardin County, Illinois (modified from Baxter and Bradbury 1980, fig. 2).

ROCKS EXPOSED AT HICKS DOME

Sedimentary Rocks

Strata at Hicks Dome are described in table 1. More detailed descriptions of the Devonian units are in Weller et al. (1952, p. 57-58), and of the Mississippian units in Baxter and Desborough (1965, p. 3-7). Figures 2 and 4 show the areal distribution of the rock units.

The central part of the dome is underlain by limestone and chert of Lower and Middle Devonian age. Identifying individual stratigraphic units and mapping contacts are difficult because of the paucity of limestone outcrops due to deep weathering and the siliceous, brecciated character of rocks within the central area. Drilling results (Brown et al. 1954, p. 873) indicate that the Clear Creek Chert, the oldest of the Devonian formations recognized on Hicks Dome, underlies the cherty clay residuum at the center of the dome. Layered chert, exposed in the walls of an exploration trench in the western part of the central area (fig. 4), may be part of the Clear Creek Chert from which the limestone has weathered. The overlying Grand Tower Limestone was not positively identified in outcrop at Hicks Dome. Weller et al. (1952, p. 58) tentatively assigned the limestone exposed at the mouth of a large ravine in the NE, Section 31, T11S, R8E and on the dumps at the Rose Mine (fig. 4, sample site 26) to the Grand Tower Limestone. However, the dark color and argillaceous character of this limestone and its proximity to New Albany shale exposures suggest correlation with younger strata, probably the Howardton Member of the Lingle Formation as defined by North (1969, p. 22-25).

The New Albany Shale Group of Devonian to Mississippian age occupies a low belt surrounding the central area and crops out at several places in streams and road cuts. The beds dip outward from the central area at 10° to 25°; dips are steepest on the north and northwest flanks. The New Albany overlies the Lingle Formation (Baxter et al. 1967).

Overlying the New Albany is the Springville Shale (not differentiated on fig. 2 or 4), 10 to 25 feet (3 to 8 m) thick and well exposed only where Hicks Branch breaches the western flank of the domal structure. Conformably overlying the Springville is the Fort Payne Formation, which consists of approximately 550 feet (170 m) of chert, siliceous limestone, calcareous siltstone, and dark shale. In the Hicks Dome area, much of the calcareous material has been leached, leaving a residuum of chert, silt, and clay. The beds of the Fort Payne dip away from the dome in a manner similar to that of the underlying New Albany, and form an outer rim or escarpment. Typical leached, siliceous beds of the Fort Payne are well exposed in an abandoned quarry on the east flank of the dome in the NW SE NW 1/2, Section 32, T11S, R8E.

Intrusive Rocks and Breccias

Clearly intrusive rocks at Hicks Dome include one ultramafic dike and the intrusions classified in this report as vent and carbonatitic breccias (fig. 4). The ultramafic dike, named the Robinson Dike by Weller et al. (1952, p. 71), is known chiefly from an old prospect pit on the east flank of the dome, where it is weathered to a residuum of soft, micaceous material. Where intersected by a shallow, 1950s exploration trench west of the pit, the dike strikes N57E, in marked contrast to the N15W to N30W

Table 1 Strata at Hicks Dome (from Baxter and Desborough 1965)

Unit	Description	Thickness ft	Thickness m
Mississippian System			
Valmeyeran Series			
Fort Payne Formation	Calcareous siltstone; silty, dark limestone; cherty limestone; chert.	550	170
Springville Shale	Gray to greenish gray shale.	10–25	3–8
Mississippian-Devonian System			
Upper Devonian and Kinderhookian Series			
New Albany Group	Dark gray to black, carbonaceous silty shale.	395+	120+
Devonian System[a]			
Middle Devonian Series			
Lingle Formation	Cherty, partly argillaceous limestone.	106	32
Grand Tower Limestone	Light-colored, cherty limestone, sandy at base.	144	44
Lower Devonian Series			
Clear Creek Chert	Calcareous dolomite and chert; scattered, fine sand grains; base not exposed.	?	?

[a] Based on Marietta Oil Co.—Fricker No. 1 test in Section 30, T11S, R8E.

Figure 5 Shatter breccia dikes in the Fort Payne Formation. (a) Sample site 52, SW NW NW SW, Sec. 32, T11S, R8E. Dip indicator near center of photograph is 4 inches square. (b) Sample site 43, near center SW NW NW, Sec. 31, T11S, R8E. Dip indicator is for scale.

strike of most other ultramafic dikes in the Illinois-Kentucky Fluorspar District.

The Joiner breccia on the west flank of the dome (fig. 4) was identified previously as an ultramafic dike (Weller et al. 1952, p. 71), but current investigations of heavily weathered samples have led us to conclude that the Joiner is an intrusive breccia with carbonatitic affinities.

Breccias at Hicks Dome appear to have had explosive origins, and on the basis of morphology and lithology, they can be separated into shatter breccias, vent breccias, and carbonatitic breccias. Shatter breccias are tabular dike-like bodies composed only of clasts from the immediately surrounding wall rock. Vent breccias (Heinrich 1966, p. 74) are bodies of irregular or indeterminate shape, with fragments apparently from local sedimentary rocks and some clasts that have been vertically displaced up or down. Carbonatitic breccias consist of igneous and sedimentary fragments, commonly with reaction rims, in a carbonate matrix or in an incoherent, weathered residuum that may have had a carbonate matrix. Gold (1972, p. 9-12) believes the source of such carbonate may have been CO_2-rich gases exsolved from an alkaline magma at depth.

DISTRIBUTION AND CHARACTER OF THE BRECCIA BODIES

Breccias at Hicks Dome occur in the central area of Devonian rocks in the encircling ring of New Albany shale and the surrounding Fort Payne escarpment (fig. 4). The Grant Intrusive, 0.6 mile (1 km) south of the study area in Section 6, T12S, R8E (fig. 2), crops out within the belt of Mississippian Salem Limestone. Shatter breccias typically occur in the Fort Payne and New Albany, whereas vent breccias appear to be confined to the central area. Known carbonatitic breccia exposures at Hicks Dome have New Albany host rocks. As the character of occurrence depends partly on the host rock, the following occurrence descriptions are arranged by outcrop area of the host rock. Outcrops are relatively rare downdip from the top of the Ft. Payne escarpment, where the outer boundary of the study area was placed.

Most breccia exposures are dike-like (fig. 5a) and range from a few inches (cms) to 10 feet (3 m) wide (fig. 5b). The strikes of breccia dikes plotted on a rose diagram define a crudely radial pattern (fig. 4). The measured strikes appear to cluster around three main directions, N30W, N30E, and N60E to N65E. The N30W direction approximates the strike of virtually all ultramafic dikes in the Illinois-Kentucky Fluorspar District (Clegg and Bradbury 1956); the N30E to N65E direction corresponds to regional block-faulting trends. The apparent radial arrangement, though crude, is probably real and caused by tangential stresses around the domal uplift.

The breccias are not extensively mineralized. Only seven of the approximately 40 breccia occurrences contain visually detectable mineralization. The mineralized occurrences are spatially related to the center of the dome. All four breccia localities in the central area, two of five New Albany shale breccias (sample sites 14 and 37), and a carbonatitic breccia (sample site 47) also in the New Albany outcrop belt, are mineralized. None of the approximately 30 Fort Payne breccias contains visually detectable mineralization.

The most common of the potentially economic minerals are fluorite and barite; one or both are present in all the mineralized occurrences. None of the occurrences, except those in the mined-out fluorite at the Rose Mine (fig. 4, locality 26), represents minable concentrations. Very small amounts of sphalerite and galena are found in the Pankey Breccia on the east side of the central area and in the Hamp well on the west side of the central area (Brown et al. 1954). The beryllium mineral, bertrandite, was identified in one of the New Albany shale breccias and in sample cuttings from the Hamp well. Moderate amounts of hematite, as both specularite and an earthy red powder, were noted in some siliceous breccias in the

central area and the Fort Payne rim. Previous work at Hicks Dome (Trace 1960) showed the presence of brockite and florencite in samples from the prospect trench near Hamp well. Spectrographic analyses of the yellow, brockite-bearing material showed notable amounts of rare earths (Bradbury 1960) and the presence of above-normal amounts of niobium (Trace 1960). Hall and Heyl (1968, p. 661) tentatively identified a rare-earth fluocarbonate intergrown with fluorite from the Hamp well. Spectrographic analyses of samples from the Hamp well showed above-normal amounts of beryllium (Be), niobium (Nb), thorium (Th), and rare earths (Trace 1960).

Central Area

Central area breccias may be conveniently grouped into four occurrences: Hamp breccias, Pankey Breccia, Rose Mine breccias, and a single breccia dike named the Rose Cemetery Breccia (fig. 4, locality 36). Boulders of siliceous breccia found scattered throughout the central area suggest that intrusive breccias may be widespread beneath the surficial zone of weathering.

Hamp locality The Hamp breccia locality consists of a cluster of occurrences near the Hamp well (fig. 4). The locality includes (1) the breccia 1,600 to 2,944 feet (530 to 980 m) deep in the well, (2) a small outcrop(?) of siliceous breccia (sample 17) and scattered boulders of siliceous breccia at the surface and in shallow prospect pits, and (3) a tabular, nearly vertical body of breccia revealed by trenching during prospecting in the mid-1950s.

Hamp well breccia The breccia intersecting the Hamp well is designated a vent breccia in this report. Brown et al. (1954) described this breccia as a "confused brecciated zone," that began at a depth of "1,600 feet" and "persisted to the bottom of the hole at 2,944 feet." The lowest stratigraphic horizon confidently identified was the contact of the Ordovician Decorah-Plattin and Joachim Formations at a depth of "1,815 feet" (table 2); below this, "intense brecciation confused [the identification of] lithologic units throughout [the lower] 1,100 feet." The hole bottomed in the breccia at a depth that in an undisturbed section would have been in the Knox dolomite of Cambrian to Ordovician age.

Brown et al. (1954) described the petrography of the Hamp well breccia. A summary of their description follows.

As determined from rotary drilling samples, the Hamp well breccia consisted of broken fragments of the host sedimentary strata. Strata in the upper part of the hole were apparently fractured and broken up, but more intense brecciation began at about 1,600 feet. Below 1,815 feet, clast lithologies apparently were severely mixed vertically. Brown et al. (1954, p. 893) stated that "pieces resembling Maquoketa shale were found 1,000 feet below the base of that formation," and "St. Peter type sand was found to cover more than twice its normal range."

Descriptions of thin sections of side-wall cores (Brown 1954, p. 901) indicate that the matrix of the breccia was probably finely comminuted rock and secondary quartz, suggesting a similarity to the surface exposures of siliceous breccias. Partial silicification of some dolomite fragments was noted in thin sections. The presence of secondary calcite in the Hamp well breccia was pointed out in a paragraph on mineralization (p. 897), but none was mentioned in thin-section descriptions.

Fragments of possible igneous origin were noted in the thin sections (Brown et al. 1954, p. 901). They consisted of "three brown altered fragments, possibly basic igneous" in one thin section and a fragment of quartz with apatite inclusions in two other thin sections. A zircon(?) was also noted, but it may have been a detrital grain, since rounded quartz grains, probably representing disaggregated sandstone, were relatively abundant in the lower part of the hole. An interpretation of the "possible basic igneous" fragments, not considered by Brown et al. (1954), is that they represent an ultramafic dike that had intruded the sedimentary strata prior to brecciation. The apatite occurrences, described as "one large vitreous quartz fragment with apatite" and "one good vitreous quartz fragment with included apatite and dolomite," are atypical of apatite in igneous rocks, and they may be hydrothermal. Apatite, a common mineral in alkalic and carbonatitic terrains, is characteristic of cross-cutting veins, which also have sulfides in places (Heinrich 1966, p. 176-179).

According to Brown et al. (1954), the breccia, intersected from "1,600 feet to the bottom of the well at 2,944 feet", was continuously mineralized by fluorite as breccia filling, veinlets in rock fragments, and replacement of limestone fragments. The fluorite was "opaque purple with minor translucent purple and clear." Assay values ranged from less than 1% to a high of 11% fluorite (CaF_2).

Table 2 Summary of stratigraphic units intersected in Hamp well (Brown et al. 1954, p. 892).

Formation	Depth (ft)
Lower Devonian	
Clear Creek Limestone	275
Backbone Limestone	300
Bailey Limestone	795
Silurian	
Moccasin Springs Limestone	890
St. Clair Limestone	930
Sexton Creek Limestone	942
Edgewood Limestone	1000
Ordovician	
Maquoketa Shale	1225
Kimmswick Limestone	1287
Decorah-Plattin Limestone	1817
Joachim Dolomite	2057 (?)
Dutchtown Formation	?
St. Peter Sandstone	?
Knox Dolomite	2944 T.D.

The breccia also contained various amounts of barite, minor sphalerite, and minor galena. Above the breccia was a shallower zone of fluorite mineralization in fractured rock at 310 to 330 feet. This fluorite, clear green and in "large chunks," provided a striking contrast with the fine-grained, opaque purple fluorite of the deeper breccia (Brown et al. 1954, p. 897).

Analyses performed by the U.S. Geological Survey (Trace 1960) on 25-foot (8-m) composite samples from the breccia interval showed significant amounts of Be (0.06%), Nb (0.15%), Th (0.X-%), and rare earths (0.0X+%). Hall and Heyl (1968, p. 661) tentatively identified a thorium-yttrium-bearing fluocarbonate intergrown with dark purple fluorite ("opaque purple" of Brown et al. 1954) from the breccia, and pointed out that light-colored fluorite from shallower depths in the same well lacked Th and rare earths.

Analyses for Be, performed on drill cutting samples taken at 5-foot (1.7-m) intervals and filed at the Illinois State Geological Survey, revealed Be concentrations up to 0.2% in some samples from 25-foot intervals identified as high-Be by the U. S. Geological Survey. Acid digestion of the more Be-rich samples, followed by heavy-liquid separation, achieved a 7-fold concentration of Be. Bertrandite, a Be silicate, was identified optically in the concentrate (Baxter and Bradbury 1980).

Hamp outcrop (?) The breccia outcrop (?) (fig. 4, sample site 17) is 700 feet (210 m) west of the Hamp well. The breccia is a cluster of small, soil-free, siliceous rock occurrences essentially flush with ground surface that may be partially buried boulders. Samples appear to be composed of siliceous fragments in a very fine-grained, quartzose matrix. The matrix and the siliceous fragments both contain numerous, rhombic to roughly rhombic relicts, indicating the former presence of carbonate minerals.

A few scattered boulders of the same material are found at the surface and in prospect pits at the Hamp locality. Intense silicification makes it difficult to identify the source of breccia clasts. We lumped these miscellaneous occurrences of siliceous breccia together as probable vent breccia by their association with the Hamp well breccia and similarity to other vent breccias.

Three thin sections were made from the miscellaneous surficial occurrences of siliceous breccia near the Hamp well. Thorough silicification made identification of clast origin difficult, but textural features provided clues to breccia type. Two sections showed thorough mixing of rounded clasts with unlike lithologies. We assumed these sections to be examples of vent breccia. The third section contained angular clasts of two apparent lithologic types and appeared be a shatter breccia, but this section could also have been from the marginal part of a vent breccia.

Samples collected from the breccia outcrop(?) and from boulders of breccia at the Hamp locality contained widely scattered occurrences of barite and fluorite as small cavity fillings. One thin section of breccia contained barite. In limited areas of the thin section, fragments of barite in the microcrystalline quartz matrix exhibited optical continuity with neighboring barite fragments.

Hamp trench breccias When exposed by exploratory trenching in 1956, the tabular body at the Hamp locality extended in a N24W direction for at least 260 feet (80 m) (fig. 4). At the time of this study, the breccia was no longer exposed; therefore, the following description of the Hamp trench breccias is from Bradbury's 1956 field notes.

The width of the breccia body at the base of the 20-foot (6-m) wide trench was indeterminate. In the trench floor was a central zone of brown to dark brown, loose, incoherent material. This zone, 8 inches to 2 feet (20–60 cm) wide, was bordered by a mixture of broken, gray chert in red clay. The chert and clay may have been weathered breccia, weathered host rock broken during excavation, or both. Within the central brown zone was a yellow, clayey material in lenses and stringers approximately parallel to the borders of the brown zone. The somewhat gritty yellow material was highly radioactive. The host rock exposed in the trench walls was bedded chert and siltstone, irregularly bedded from having had an original carbonate component weathered out. Whether the tabular body was originally a shatter breccia or a narrow, fracture-oriented extension of the breccia encountered in the Hamp well could not be determined.

The brown-stained breccia in the Hamp trench was an incoherent mass of rock and mineral fragments in a matrix of silt- and clay-size particles. Rock fragments were up to 3 cm in diameter and consisted of chert, siltstone, chert breccia cemented by fine-grained quartz, and a fine-granular quartzose rock. The latter consisted of scattered, rounded quartz grains in a very fine-grained quartz matrix, which we judged to be a silicified, former sandy limestone. The rock fragments cannot be confidently correlated with specific stratigraphic units. Whether significant vertical displacement of individual breccia fragments occurred could not be determined; all fragments could have come from the immediate Devonian wallrocks. Mineral fragments were aggregates of fine- to very fine-grained quartz and very similar to the cementing material of the siliceous breccias common to the area. Qualitative chemical tests indicated that the brown to dark brown staining was due to iron and manganese oxides.

The yellow, finely particulate phase contained rock and mineral fragments similar to those in the brown phase, but the yellow phase had a much lower ratio of rock fragments to fine-grained quartz aggregates. Most of the yellow material passed a 10-mesh screen (2-mm openings); more than half of it was finer than 325 mesh (.044 mm). The clay-size fraction (less than .002 mm) of the yellow material was 24% of the sample tested.

Mineral separations performed on the yellow material using bromoform resulted in heavy-mineral concen-

trates that contained 20% to 30% yellowish brown, soft, earthy pellets. The pellets were a few tenths of a millimeter in diameter and intensely radioactive. Trace (1960) identified similar pellets from other samples of the yellow material. He identified some of these pellets as an unusual yttrium- and thorium-bearing "monazite" that was later recognized as the mineral brockite (Fisher and Meyrowitz 1962), and others as florencite, a cerium-aluminum phosphate. Other components in the heavy-mineral concentrates were particles of limonite, partly pseudomorphous after pyrite, and quartz coated with limonite.

File notes from the 1956 study contained no data on the percentage of heavy minerals in the bulk sample, so no estimate can be made of the percentage of brockite and florencite in the host material. Emission spectrographic analyses indicated that up to 3.5% of total rare earth oxides was in the brockite-bearing material (Bradbury 1960); similar amounts were reported by Trace (1960, sample RDT-6). Trace also reported thorium (0.1% to 0.5%) and niobium (0.01% to 0.05%) in RDT-6. No other potentially economic minerals were recognized in the heavy-mineral separates; however, the three samples collected during excavation were from the most radioactive parts of the breccia body (yellow, finely granular material). Fluorite, barite, or other ore minerals may be present elsewhere in the vein-like exposure.

A second trench, oriented at a slightly different bearing and located 300 feet (90 m) east of the first, revealed residual chert and red clay that contained a few small, irregular masses of the yellow, gritty material. The second trench exposure was interpreted as the residuum of country rock that had been invaded by stringers of the same material exposed in the main trench.

The nature and components of the trench breccia indicate that it had a multistage origin. The identity of fragments in the breccia suggests a silicified shatter breccia. Its present incoherent nature further suggests that the breccia may have been cemented at one time by a carbonate mineral, indicating a multiple origin similar to that of the Rose Mine mixed breccia described below. The iron manganese staining of the tabular body suggests the prior presence of a ferruginous-manganiferous carbonate, probably a dolomite. The yellow, thorium-bearing material is distinctly different in color and particle size from the bulk of the breccia. It cannot be determined in this study whether the thorium-bearing material existed as vein-like bodies that were disturbed by the emplacement of the breccia or was emplaced later in fractures in the siliceous breccia.

Pankey vent breccia The locality of Pankey vent breccia (fig. 4, samples 20, 22, 24) is a 200- by 300-foot (61- by 92-m) knob near the northeast edge of the central area. The site is covered with abundant blocks of breccia. Individual blocks are composed of both hard, dense breccia and porous breccia. Rock fragments in the breccia are cemented together by fine-grained, drusy quartz.

Figure 6 Texture of the Pankey Breccia, a siliceous vent breccia in lower Devonian chert. Sample site 20, SE NW, Sec. 30, T11S, R8E. (Mag. approx. 4.25x).

The Pankey Breccia is composed of angular to subrounded fragments of completely silicified limestone and chert in a matrix of finely comminuted rock and microcrystalline to crystalline quartz (fig. 6). The porous breccia, much less abundant than the more typical dense breccia, consists of silicified rock fragments in an open framework lined and cemented by drusy quartz. The size of these silicified limestone and chert fragments ranges from several centimeters to an arbitrary lower limit. Below this size they are indistinguishable from the matrix. Correlating the lithology of the fragments with the specific formations from which they came is difficult because of the silicification; however, individual fragments can be classified by texture as (1) even-grained novaculitic, (2) uneven-grained microcrystalline, (3) fossiliferous, (4) faintly laminated, and (5) laminated.

Probable Devonian chert fragments, classified primarily as novaculitic or microcrystalline and interpreted to be detrital, contain scattered grains of quartz, 20 to 100 µm. Some fragments, especially some of those classified as novaculitic, contain rhomb-shaped cavities, interpreted as sites from which carbonate minerals have been weathered or leached out. In some instances, these cavities have been filled by other minerals, such as coarsely crystalline quartz or barite. Other rhomb-shaped cavities, 40 to 60 µm, contain extremely fine-grained, yellowish to brownish ferruginous material that is the probable alteration product of an iron-rich carbonate. Some breccia fragments are characterized by irregular areas of brown to red, iron oxide staining.

Even-grained novaculitic chert Even-grained, novaculitic chert refers to fragments composed predominantly of homogeneous, even-grained cryptocrystalline (<10 µm) quartz. The even-grained novaculitic chert fragments are quite similar to novaculite from the Lower Devonian Clear Creek and Grassy Knob Formations in Union and Alexander Counties in southwestern Illinois. The term novaculite has been used in southern Illinois probably because of the similarity of some Illinois Devonian chert units to the Arkansas Novaculite of the Ouachita Mountains in Arkansas.

Uneven-grained microcrystalline chert Fragments of uneven-grained microcrystalline chert are composed of a variable mixture of cryptocrystalline and microcrystalline quartz. An interlocking character of the quartz crystals becomes apparent with increasing grain size. Under crossed polars the appearance of the uneven-grained chert is intermediate between the bluish gray of even-grained novaculite fragments and the lighter gray of the microcrystalline breccia matrix. Uneven-grained microcrystalline chert is known from both the Clear Creek and Grassy Knob Formations in Union and Alexander Counties.

Fossiliferous fragments Fossiliferous fragments are composed of cryptocrystalline to microcrystalline quartz, but faint relict outlines of the original allochemical components of a biocalcarenitic limestone are preserved. The biocalcarenitic particles range from 0.1 to 0.3 mm in diameter and include fragments of echinoderms, echinoid spines, sponge spicules, ostracods, brachiopods, and minute spheres that possibly represent either oogonia, e.g., reproductive sacs of charaphytes (algae), or silicified calcispheres. Although the stratigraphic position of the original limestone is uncertain, the petrographic aspects suggest correlation with the Middle Devonian formations, possibly the Grand Tower.

Faintly laminated fragments Faintly laminated fragments are also composed of cryptocrystalline to microcrystalline quartz. In plane polarized light, discontinuous, wavy laminations are faintly discernable, but whether the lineations are due to the orientation of former allochems or to microbedding features cannot be determined.

Laminated fragments Laminated fragments are composed of cryptocrystalline to microcrystalline quartz marked by closely spaced brown laminations. These fragments were probably derived from strata that originally consisted of either shaley, fine-grained limestone or alternating beds of chert and shale.

Breccia cement The cement of the Pankey Breccia is composed of cryptocrystalline to microcrystalline quartz, with optical extinction units of 10 to 40 µm, and finely comminuted siliceous rock. Coarse, euhedral quartz crystals line cavities in most of the breccias. Many specimens exhibit more than one generation of cement, recognizable by subtle color and textural differences, and there are recognizable multigenerational breccia fragments. The small rhomb-shaped cavities, presumably representing former carbonate minerals are also found in the cement where, again, the cavities may be empty or may contain quartz, barite, or ferruginous material.

Abundant coarse barite occurs as open-space fillings in the Pankey Breccia near the south end of the exposure area (sample site 24, fig. 7). The only fluorite observed was in 1-mm colorless cubes in a small vug. In 1962 the International Minerals and Chemical Corporation attempted to drill a few shallow core holes in the Pankey Breccia. Difficult drilling conditions and poor core recovery caused by frequent mud seams and intervals of loose, sandy or rubbly material led to abandonment of the project. Company logs indicate that the recovered core from beneath the barite-bearing zone contained veins and patches of barite, minor sphalerite and galena, and minor colorless fluorite.

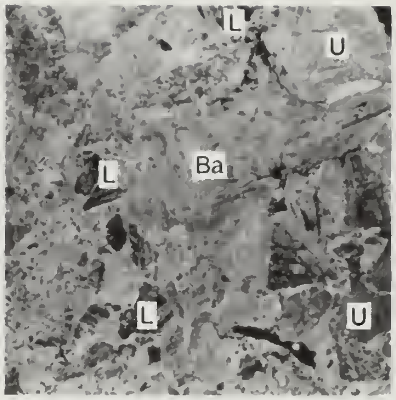


Figure 7 Barite (Ba) mineralization in siliceous vent breccia at south margin of the Pankey Breccia. Sample site 24, NW SE NE NW, Sec. 30, T11S, R8E. Mixture of laminated (L) and unlaminated (U) breccia fragments. (Mag. approx. 4.25x).

Rose Mine breccia The Rose Mine breccia occurs in the abandoned fluorite mine on the eastern flank of the dome near the New Albany shale contact (fig. 4, locality 26). The breccia is composed of altered limestone and/or chert fragments with fluorite in open spaces. It occurs as broken fragments on the old mine dumps and as a breccia dike within a 50-foot-deep drag-line excavation. The dike trends N55E, is 4 feet (1.2 m) wide, and contains partly silicified limestone fragments and fluorite mineralization. At the northeast end of the pit, the dike is strongly weathered; leaching of calcite from partially silicified limestone fragments left porous frameworks of acicular quartz.

Little information remains about that portion of the Rose ore body mined underground at this locality. Weller et al. (1952) described the ore as containing both massive fluorite and discontinuous fluorite veins and pockets with no well defined walls. Some of the fluorite was of optical quality. The described character of ore in the underground workings contrasts with the scattered nature of the mineralization within the breccias. Perhaps the major portion of the fluorite in the ore body was deposited as discontinuous fissure fillings in the host limestone, which subsequently weathered to residually concentrated clay and chert in poorly defined wall rock. Such deep weathering and the reported discontinuous nature of the veins suggest a strongly fractured area.

Petrographically, the Rose Mine breccia (fig. 8) is classified as a shatter breccia. Three types of breccia—siliceous, calcareous, and mixed—are petrographically divisible in the Rose Mine locality.

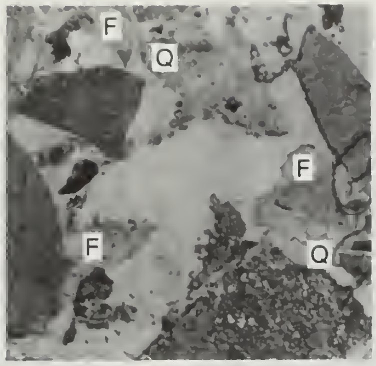


Figure 8 Texture of Rose Mine breccia, a mineralized siliceous breccia in Lower Devonian. Sample site 26, NE NW SE, Sec. 30, T11S, R8E. Breccia fragments with interstitial quartz (Q) and fluorite (F). (Mag. approx. 4.25x).

Siliceous breccia Siliceous breccia at the Rose Mine is composed of fragments of chert and silicified limestone cemented together by fine-grained quartz. The silicification of the limestone fragments makes it difficult to recognize their original stratigraphic position, but there is no evidence to suggest that the fragments came from other than immediate wall rock limestone.

Calcareous breccia Calcareous breccia found on dumps at the Rose Mine consists of limestone fragments in a matrix of coarse crystalline, white calcite. The fragments are composed of fine to coarse skeletal debris in a matrix that ranges from microsparite to dark, argillaceous and/or organic-rich calcisiltite with clusters of pyrite crystals and scattered quartz grains. The lithology of the breccia fragments suggests that they came from the Lingle Formation, the apparent host rock at the Rose Mine.

Mixed breccia Mixed breccia consists of a mixture of calcareous and siliceous material. Fragments of coarsely crystalline calcite, dark brown to black chert, and an earlier siliceous cement occur in a matrix that consists of a mixture of fine-grained calcite and fine-grained siliceous cement. Some of the chert fragments also have siliceous cement attached to one or more faces. Whether the matrix calcite is finely ground, preexisting calcite, or has crystallized in place could not be determined. Both comminuted and hydrothermal calcite are probable. A later, fine-grained calcite appears to be associated with a postbreccia episode of quartz-fluorite mineralization. The components of the mixed breccia suggest that it was formed by yet another phase of brecciation that involved preexisting occurrences of both calcareous and siliceous breccia.

The breccia dike, once exposed in the bottom of the drag-line excavation, is composed largely of brown fossiliferous limestone fragments, but the breccia dike may be considered "mixed" because it appears to have undergone partial silicification. A sample of the dike taken from the west wall pit contained dark shale fragments in addition to brown limestone, neither of which appears to be silicified. Since the dike remnant and the limestone and chert fragments from dump samples were assignable to the Lingle Formation, breccia found at the Rose Mine site is presumed to be shatter breccia.

Among the exposed breccias of the central area, Rose Mine breccias were the most extensively mineralized. In the Rose Mine site, relatively light-colored fluorite (colorless, white, green, and purple), with calcite and quartz, was deposited in open spaces in the breccia. Barite is found interstitial to fluorite in a thin section. No sulfides were seen megascopically or in thin section, but samples taken for this study may not be representative of the Rose ore body.

Rose Cemetery Breccia A fourth occurrence of breccia was found just west of Rose Cemetery at the southeast end of the central area. Blocks of siliceous breccia are aligned in a N45E direction on a gentle hill slope, possibly indicating a breccia dike. Near its southwest end, the alignment is interrupted by a south-flowing stream, on the west side of which stands a breccia dike, offset about 5 feet (1.5 m) southward from the alignment of the blocks. No slickensides were exposed, and we are uncertain whether the offset in alignment is due to strike-slip faulting or a normal fault of a nonvertical dike, or whether the two block alignments are separated, en echelon segments of the same inferred breccia dike.

The Rose Cemetery Breccia boulders do not appear to be mineralized. Minor fluorite, however, was noted in a small, poorly exposed outcrop of fractured, but otherwise normal-appearing strata a few feet away from the apparent breccia dike.

New Albany Group Belt

Breccia bodies recognized within the belt of New Albany shale include shatter and carbonatitic breccias. Compared with the adjacent belt of the Fort Payne rim and the central core of Hicks Dome, carbonatitic breccias are more apt to be exposed within the shale belt because less differential resistance to weathering occurs between the carbonatitic breccia bodies and wall rock.

Shatter breccias Four shatter breccias observed within the belt of New Albany shale (fig. 4) are nearly vertical, dike-like bodies. The geometry of a fifth was indeterminable because of poor exposure. All have northwesterly strikes, ranging from N30W to N50W. Widths range from 4 inches (10 cm) to 10 feet (3 m). The more highly siliceous shale breccias weather positively, but shale-clast breccias with calcite cement and fluorspar are less resistant than their host rocks.

Siliceous shatter breccias The siliceous shatter breccias in the New Albany shale contain shale fragments that have been replaced extensively by cryptocrystalline quartz. The original shale lithology is revealed by the layering of carbonaceous material in the fragments. Mottling in some shale fragments is interpreted as evidence of bioturbation. The degree of brecciation ranges from mere veining of the shale by microcrystalline quartz to

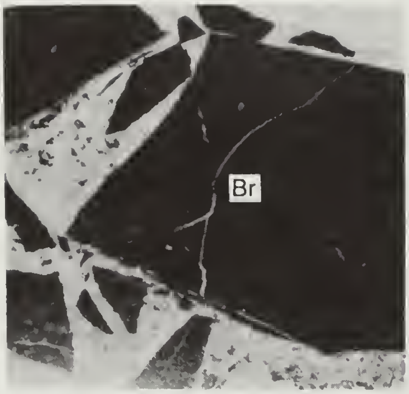


Figure 9 Calcareous shatter breccia composed of fragments of New Albany Shale (Br) with interstitial quartz, fluorite, and calcite. Sample site 14, SE NW NW SE, Sec. 25, T11S, R7E. (Mag. approx. 4.25x).

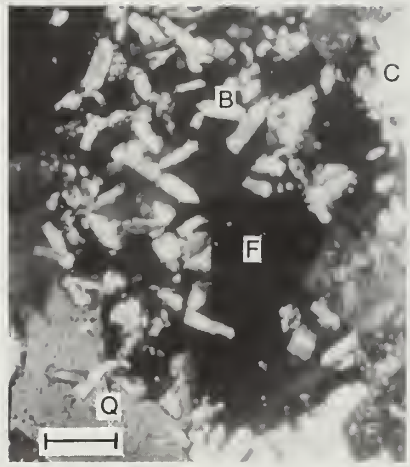


Figure 10 Sample site 14. Bertrandite (B) with quartz (Q), fluorite (F), and calcite (C). (Bar scale = 0.1 mm).

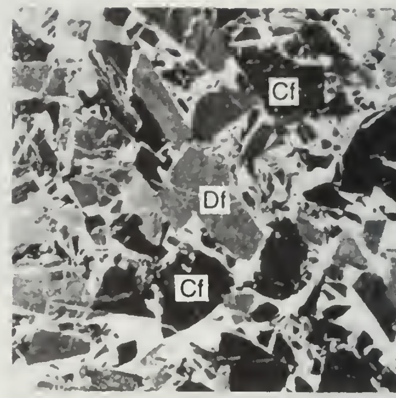


Figure 11 Shatter breccia composed of mixed fragments of carbonaceous shale (Cf) and lighter colored dolomitic fragments (Df) with interstitial calcite (C). Sample site 37, center W line, NE SE NE, Sec. 31, T11S, R8E. (Mag. approx. 4.25x).

discrete, rotated fragments of silicified shale in microcrystalline to crystalline quartz cement.

Calcareous shatter breccias The calcareous breccias from the New Albany Shale are composed of fragments of laminated, carbonaceous, dolomitic, dark brown shale variously oriented in a carbonate cement (figs. 9, 10, 11). An X-ray diffraction analysis of carbonate cement from a prominent exposure (sample site 37) showed 96% calcite and 4% ferroan dolomite.

In one of the breccias, microcrystalline quartz is found as selvages along some edges of shale fragments, and as scattered, small aggregates in the carbonate matrix. The partial selvages of microcrystalline quartz and scattered fragments of similar material in the matrix suggest that the calcareous breccia was emplaced along an existing fracture zone that contained earlier quartz veinlets.

In another calcareous breccia, early quartz selvages were not observed, but fine granular quartz is present in the matrix. In this breccia, the primary matrix is very fine carbonate (0.1 to 0.2 mm), containing finely ground shale. The quartz and a fine-grained calcite (0.5 mm) appear to vein and replace the matrix in places.

An X-ray diffraction analysis of the "shale" clasts (fig. 11) in the prominent calcareous shale breccia dike at sample site 37 (fig. 4) showed abundant feldspar and no clay minerals. A sample from a narrow shale breccia dike, 3 inches (8 cm) wide and 25 feet west of carbonatitic breccia sample site 47, contained some feldspar and remaining illite. Analyses of two outcrops of apparently unaltered bedded shale, one on the west and the other on the southeast side of the dome, detected no feldspar; illite contents ranged from 49% to 70% (John Fox, ISGS, personal communication, 1987). An X-ray diffraction analysis of a sample that appeared to represent "normal" shale at a depth of 146 feet (45 m) in core 11IL (fig. 4) showed no clay minerals. The minerals identified, and whose estimated amounts were determined from X-ray peak heights, were dolomite, plagioclase, and orthoclase (each about 20% to 40% of the sample) and quartz and pyrite 5% to 15% each (Randall E. Hughes, ISGS, personal communication, 1990). The plagioclase was almost pure albite. More analytical data are needed before definitive statements can be made concerning alteration of the shale of the New Albany Group around Hicks Dome, but the preliminary results suggest that shale feldspathization is related to igneous activity and brecciation-mineralization episodes.

Of the five New Albany shale breccia occurrences, only the two calcareous breccias were mineralized. One contained small, irregular masses of fluorite (primarily the nearly opaque, dark purple variety) in the calcite matrix. Tabular crystals, 0.1 mm long (fig. 10), were identified optically and by X-ray diffraction as the beryllium silicate, bertrandite (Baxter and Bradbury 1980). They are enclosed in the fluorite and the adjacent fine-grained quartz. The quartz appears to have replaced the fluorite and to have enclosed the bertrandite crystals in the fluorite. The mineralization episode apparently consisted of calcite, followed by fluorite-bertrandite, and then by quartz. The episode also appears to have been associated with a period of fracturing that followed formation of the host calcareous breccia.

The other calcareous breccia (sample site 37), the one with strong feldspathization of the shale, contained only coarse barite that replaced matrix calcite. No fluorite-bertrandite-quartz episode was observed.

Carbonatitic breccias All carbonatitic breccia occurrences within the immediate study area at Hicks Dome were found in the New Albany Shale belt. Four carbonatitic dikes have been observed at two outcrop localities (fig. 4). In addition, because of its proximity to the dome, the Grant Intrusive located approximately 2 miles south of the apex was sampled.

Joiner Dike Weller et al. (1952, p. 71) noted that the Joiner Dike near the Fort Payne-New Albany contact on the southwestern flank of the dome (fig. 4) comprises two separate dikes: a "main dike exposed for 125 feet in [a] gully trending northeast, [and] also [a] 12- to 18-inch dike 40 feet north of main dike." Only a single occurrence of micaceous residuum can now be found at the site. Both walls of the narrow dike and the north wall of the main dike were black shale; the south wall of the main dike was not exposed. The strike of the narrow dike was measured as N46W; that of the north wall of the main dike was N50W. The narrow dike and the northern one-third of the main dike were described by Weller et al. (1952) as weathered "clayey material" containing abundant mica. The southern two-thirds of the main dike contained abundant inclusions of shale and a fine-grained, siliceous rock, but little or no mica. The two material types in the main dike were described as being separated by a transition zone in which the mica content decreased while the abundance of rock inclusions increased.

A sample of presently exposed micaceous residuum and a sample, labeled "weathered dike rock" in the ISGS files and taken in 1952 from "10 feet south of north margin of main dike," were examined microscopically using crushed samples and oil immersion techniques. Both samples consist of cryptocrystalline weathering products that contain abundant light brown mica and fragments of igneous and sedimentary rocks. Feldspathic rock fragments are not numerous, but feldspar grains are common in random oil immersions. Most of the feldspar grains have refractive indices characteristic of orthoclase, and are probably from the same source as the feldspathic rock fragments. A few small fragments consisting of untwinned albite and clear, green epidote were observed, and a few grains of apatite were present in most oil immersions. Black shale, sandstone, siltstone, and chert fragments are common. Limestone fragments may have been weathered out.

Core hole intercept A vertical core hole in the New Albany shale (core 11IL, Bergstrom et al. 1980, p. 10), about 1000 feet (300 m) southeast of the Joiner Dike exposure, penetrated three narrow stringers of dolomitic breccia believed to be similar to the parent material of the Joiner Dike residuum. The breccia was intersected at depths of 81, 143, and 193 feet (24.7, 43.6, and 58.8 m). The widest stringer averaged 1.5 inches (3 cm) and had irregular walls of fractured and brecciated black shale. The remaining two were 0.5 inches (1 cm) wide or less. The breccia stringers were gray or white with a slight greenish tinge. Except for black shale fragments and the carbonate matrix, flakes of biotite were the only macroscopically recognizable components in the breccia. A thin section of one of the breccia stringers revealed a mass of very fine-grained carbonate with clasts of biotite and extensively altered minerals and rock fragments. Most of the alteration consists of secondary carbonate; however, other alteration products, too fine grained to be identified, are present. Virtually all clasts have reaction rims of cryptocrystalline material that is white in reflected light and nearly opaque brownish by transmitted light, indicating a reaction with the carbonate.

Most of the biotite, medium brown where unaltered, has undergone some alteration. Many flakes are bent and most are 5 mm long or less, but a few reach 20 mm. Many other clasts have shapes similar to crystals of mafic silicates but no remnants of the original mineral. Other clasts are rounded or subrounded. A few masses of clear, polycrystalline carbonate may be limestone fragments. Two or three fragments of chert are present. All clasts except the biotite flakes and the shale fragments bordering the stringer are small (2 to 0.1 mm wide). The small size of the clasts probably facilitated their extensive alteration. Albite-carbonate veinlets with minor amounts of quartz and orthoclase transect the breccia. Feldspar also occurs as rims around some shale fragments and as a component of a minor, secondary breccia matrix. The secondary matrix consists chiefly of a mixture of carbonate and finely comminuted shale and is somewhat lighter in color than the primary matrix. Some masses of rebrecciated, primary matrix within the secondary matrix are highly irregular and suggest that either the primary matrix may not have been completely indurated or that the secondary matrix formed by replacement. Carbonate-quartz veinlets without feldspar also occur in the breccia.

The introduction of the feldspar was evidently related to an episode of fracturing that closely followed the original breccia emplacement. The aggregates of albite and epidote, noted in the Joiner Dike material, are probably related to this secondary albite.

Late fluorite-quartz-carbonate veinlets cut the carbonatitic breccia that intrudes New Albany shale in the drill core; veins and veinlets of the same minerals were fairly common throughout the core.

Dikes on south flank of Hicks Dome An exposure of carbonatitic breccia (fig. 4, sample site 46, 47), discovered during this investigation, consists of micaceous breccia in shale in the small stream that flows along the south flank of the dome. A fracture zone, 30 to 40 feet wide (10-14 m), contained a 3-foot (0.9-m) wide, deeply weathered, soft, micaceous dike between shale walls, and a dike of micaceous breccia, about 2 feet (0.6 m) wide, protruding several inches from the creek bank about 15 feet (4.5 m) west of the deeply weathered dike. Several narrow shale-breccia dikes and silicified, ferruginous

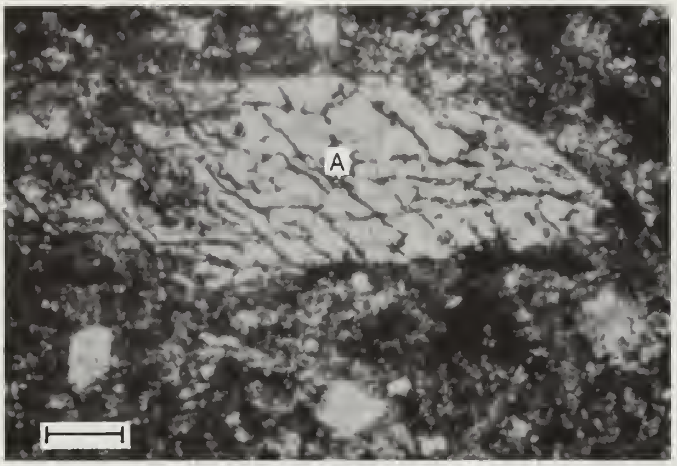


Figure 12 Photomicrograph of thin section of carbonatitic (sideritic) breccia dike (site 47) showing former amphibole crystal (A, in center of field). The crystal is completely replaced by fine-granular biotite, but recognized by characteristic cleavage pattern preserved by lines of magnetite grains (mag. approx. 4.25x).

zones in the shale occur within the fracture zone. All dikes and silicified zones were approximately parallel, with strikes of about N30W and essentially vertical dips.

The resistant dike contains a variety of mineral and rock fragments, both igneous and sedimentary, in a matrix of fine-grained, dark brown carbonate, identified as siderite by X-ray diffraction. Of the mineral fragments, only apatite and light brown mica retain their original character. Some of the mica crystals are relatively unaltered; however, most are partly replaced by chlorite and carbonate. Apatite is present as abundant, clear, glassy, euhedral and anhedral grains up to 0.5 mm in diameter. Former amphibole crystals, recognized by characteristic cleavage patterns preserved by lines of magnetite grains (fig. 12), are completely replaced by fine-granular biotite. Other now unidentifiable minerals were replaced by fine-grained carbonate, with or without serpentine. Some crystal outlines suggest pyroxene and olivine. Within some altered crystals, lines of fine magnetite grains vaguely suggest pyroxene cleavage and olivine crack patterns. Feldspar is relatively common in the breccia, both as single crystal fragments and as the essential mineral in rock fragments up to 2 to 3 cm across. Most of the feldspar is relatively unaltered orthoclase, but albite-oligoclase (An10) is fairly common. The feldspathic rock fragments range from fine to medium grained; some contain quartz. Former ferromagnesian minerals in the rock fragments are completely replaced by carbonate. Sedimentary rock fragments are common in the outer portions of the dike, but less common in the interior. Sedimentary rock clasts recognized are black shale, siltstone, and chert(?). Fragments altered to carbonate with various amounts of serpentine and other alteration products may represent ultramafic rock types (Clegg and Bradbury 1956, Koenig 1956).

The deeply weathered dike is essentially a soft mass of extremely fine-grained weathering products and abundant flakes of mica. When gently disaggregated with a mortar and pestle and washed with water, the mass yielded a few recognizable igneous rock fragments, some mineral fragments, and much fine-grained material. Microscopic examination under the binocular microscope, supplemented by oil immersion techniques, revealed the following igneous rocks (1) a fragment of rhyolite composed of extremely fine-grained orthoclase with quartz phenocrysts, (2) an aggregate of albite veined by barite, and (3) an aggregate of oligoclase with minor biotite and a few grains of quartz. Monomineralic grains observable under the binocular microscope and identified by oil immersion methods include light brown mica flakes (generally about 5 mm across) and clear, glassy, grains of apatite (generally 1 mm or less). One aggregate of apatite crystals measured 1 cm long. The extremely fine-grained material retained in the washed samples consists chiefly of cryptocrystalline alteration products. Identifiable minerals include abundant light brown mica, a few grains of feldspar, and rare quartz and apatite. The intensely weathered condition of the rock left little evidence of its original character; however, the presence of abundant light brown mica, appreciable apatite, and feldspathic rock fragments indicate a genetic relationship to the weather-resistant dike. The deeply weathered dike probably had a nonsideritic matrix, possibly calcite.

Mineralization in the sideritic breccia consisted of a few narrow, fluorite veinlets as fracture fillings. Fluorite was also identified in the same breccia as occasional inclusions within light brown mica crystals and, as such, is probably a primary mineral. Barite was identified optically in a sample from the deeply weathered dike (sample site 46) as a veinlet cutting in a small (3 mm) aggregate of albite. The failure to detect barium (Ba) in a spectrographic analysis of sample 46 indicates that barite in the dike occurs nonuniformly and probably in minor amount.

Grant Intrusive

The Grant Intrusive (fig. 2), located in the NW NW, Section 6, T12S, R8E, approximately 0.6 mile (1 km) south of the top of the Fort Payne ridge (Baxter and Desborough 1965, plate 1), is within the belt of Mississippian Salem Limestone that encircles Hicks Dome. The breccia is exposed as a ledge about 5 feet (1.5 m) thick and 20 feet (6 m) long on the southeast bank of a ravine. A cluster of boulders of the similar material occurs across the ravine. No country rock crops out immediately near the intrusive. Boulders and cobbles of a siliceous breccia are abundant up the ravine from the Grant Intrusive for a distance of about 150 feet (45 m), from which point a train of scattered boulders extends up the hillside.

The Grant Intrusive (fig. 13) is a breccia characterized by fragments and crystals of biotite and brown hornblende 1 cm or more across, fairly numerous lapilli, and

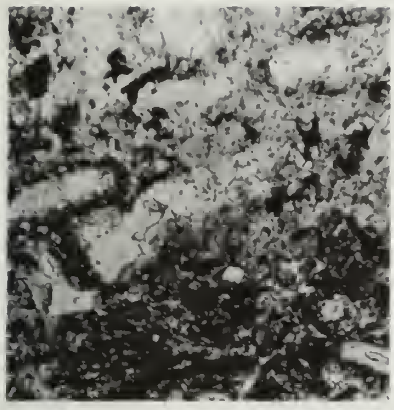


Figure 13 General texture of the Grant Intrusive, a carbonatitic breccia. Sample site 5, SW NW NW, Sec. 6, T12S, R8E. (Mag. approx. 4.25x).

fragments of various igneous and sedimentary rocks in a calcite-dolomite matrix. Apatite and a green pyroxene are found in thin sections. Many original mineral grains are partly to completely replaced by serpentine and/or carbonate.

The lapilli (fig. 14), up to 8 mm across, are roughly circular to oval and have smooth outer edges. Lapilli cores are fragments of feldspathic rock or coarsely crystalline biotite or hornblende. The biotite and most of the hornblende cores are single crystals but some of the hornblende may be polycrystalline, as in figure 14. The lapilli rims are now a fine-grained mass of carbonate clouded with alteration products, scattered grains of apatite, and accessory minerals with a high refractive index. Vague lath shapes in the carbonate suggest former biotite flakes. The lath shapes are preferentially oriented roughly tangential to the lapilli cores.

Recognizable rocks include fragments of weakly altered aegerine syenite up to 5 cm long and siliceous sedimentary rocks with reaction rims. Other igneous rock fragments are replaced by carbonate to such an extent that only remnants of feldspar point to their igneous origin. Some aggregates of fine-grained carbonate probably represent unreplaced carbonate rock fragments. The reaction rims on siliceous fragments are greenish-white in reflected light and include carbonates, scattered grains of epidote, and an unidentified, nearly opaque substance. Not to be confused with lapilli, reaction rims are a part of the fragments on which they occur. The outer boundary of the reacted fragment is that of the original fragment, and the altered rim fades into the unaltered core. Lapilli rims are clearly coatings, displaying smoothly rounded outer boundaries and sharp contacts with the fragments that they coat.

The breccia matrix is largely fine-grained calcite and dolomite clouded with finely ground rock and mineral fragments. An acid etch of a polished surface of the breccia reveals a considerable proportion of insoluble material in the matrix, but most of the noncarbonate material is so finely comminuted or altered that it is indeterminate in thin section. The overall greenish color of the matrix suggests the presence of alteration products, such as epidote, chlorite, or serpentine.

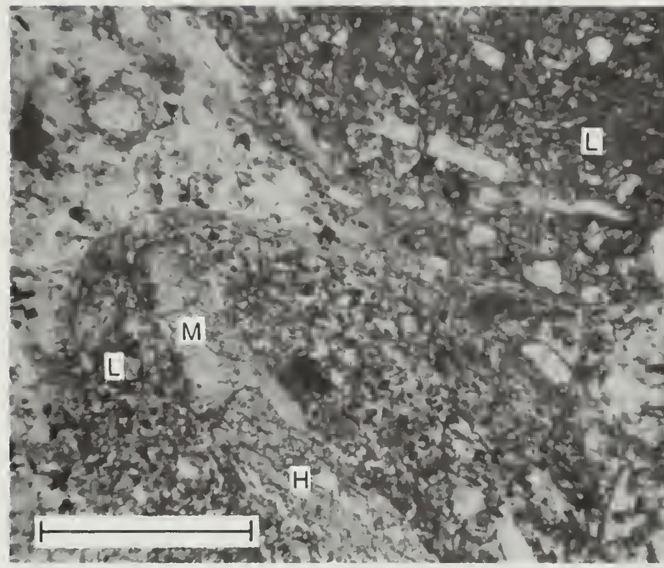


Figure 14 Photomicrograph of thin section of Grant Intrusive (site 5) showing a lapillus (L) cored by grain of hornblende (H, with characteristic cleavage) partially replaced by mica (M). (Mag. approx. 3x).

Staining tests to determine the distribution of calcite and dolomite suggest that dolomite was the first carbonate deposited. Most of the carbonate replacing rock and mineral fragments appears to be dolomite. Calcite, on the other hand, is limited largely to the matrix, but it may invade rock and mineral fragments to a lesser extent.

The boulders of siliceous breccia exposed in the ravine above the Grant Intrusive consist of rock fragments about 0.25 inches (0.63 cm) in maximum diameter. These fragments are composed of cryptocrystalline quartz (10 µm or less in diameter) that is in a brownish matrix of quartz, cryptocrystalline to very fine-grained and up to 30 µm long (fig. 15). Remnants of carbonate minerals, generally less than 0.05 mm in diameter, are scattered sparsely through the cement. Relicts of rhombohedral carbonate crystals, typically 0.1 mm on an edge, are common. They are generally outlined by iron oxide surrounding cryptocrystalline quartz stained by the iron oxide. Materials of igneous origin, or evidence of their former presence, are completely lacking in the siliceous breccia. The parent

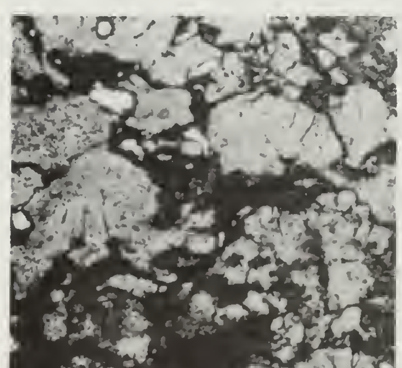


Figure 15 Silicified limestone breccia in the upper part of the Salem Limestone and up gully from the Grant Intrusive. (Mag. approx. 4.25x).

material of the siliceous breccia may be the lower part of the Salem Limestone, the country rock in the vicinity of the Grant Intrusive (Baxter et al. 1967, plate 1). The lower part of the Salem Limestone contains argillaceous, silty, dolomitic, and cherty beds (Baxter et al. 1967, p. 9) that could have provided the components of the siliceous breccia.

Fort Payne Rim Shatter Breccias

The greatest number of breccia bodies (approximately 30 observed) occur in the Fort Payne Formation (fig. 4). All were identified as shatter breccias. Most are nearly vertical, dike-like bodies. Two or three breccia outcrops consist of networks of narrow breccia veins in apparently normal bedded strata. Other breccias occur as concentrations of boulders, many of which are roughly linear boulder trains that presumably represent dikes. The shatter breccia dikes range from a few inches to 10 feet (3 m) wide. Most of the dikes are thoroughly silicified and many are exposed as free-standing, reeflike bodies, some up to 15 feet (4.5 m) high. Varying widths of silicified wall rock are incorporated as part of the resistant reefs. An extreme example of wall-rock silicification is found in one free-standing, wall-like exposure (sample sites 9, 10), 8 inches (20 cm) wide. The exposed wall contains a zone of breccia only 4 inches (10 cm) wide in its central part. Intersecting this same wall at a 90° angle is a weather-resistant, silicified zone of closely spaced, vertical fractures that contains a vein of breccia only 1 inch (2.5 cm) wide along one of the fractures.

Several dikes in the Fort Payne show one or more offsets up to 20 feet (6 m) normal to their strikes. The actual fault plane is exposed on only one outcrop, however. In this instance, horizontal slickensides observed on a rock face were normal to the strike of the dike.

Petrography The fragments within Fort Payne breccias are composed of cryptocrystalline to microcrystalline quartz and are enclosed in a matrix that appears to consist of finely comminuted rock cemented by microcrystalline quartz. Later precipitation of quartz in cavities has produced crystals up to 1 or 2 mm long. Individual clasts, subangular to subrounded, are as much as several centimeters wide. The clasts exhibit variable textures, all of which are also found in the host Fort Payne Formation. Three main lithologic clast types occur: (1) homogeneous, cryptocrystalline to microcrystalline chert, (2) laminated chert, and (3) mottled chert.

Homogeneous, cryptocrystalline to microcrystalline chert Homogeneous chert fragments range from light to medium tan, depending on the amount of iron staining. In plane-polarized light, the major inhomogeneities are minute, opaque, ferruginous rhombic and cubic areas (10 to 40 m across) and irregular ferruginous speckling. With crossed polars, the rhombs and cubes appear to be composed of cryptocrystalline and microcrystalline quartz, with the former predominant. The chert fragments also contain scattered quartz grains (40 to 80 μm) that are considered to be detrital grains.

Laminated chert Laminated chert fragments ordinarily have a greater proportion of microcrystalline quartz relative to cryptocrystalline than the more homogeneous chert fragments. The irregular and closely spaced dark laminations represent the argillaceous material in the original sediment. The laminated cherts also contain more detrital quartz grains than the homogeneous chert fragments.

Mottled chert Mottled chert fragments are relatively rare. This feature, thought to be related to bioturbation of the original sediment, is characterized by irregular light and dark brown mottling.

Breccia cement The breccia matrix is composed of finely comminuted rock and a microgranular quartz cement. Late fine- to coarse-grained quartz lines or fills open spaces. Microcrystalline matrix material also occurs as fragments in the breccia, attesting to two or more episodes of brecciation. Microgranular yellowish carbonate is present locally in small patches or intimately mixed with the microgranular quartz. Hematite is present in moderate amounts in a few breccias, as platy crystals and as the red, finely divided variety that imparts a red color to the breccia.

Robinson Ultramafic Dike

The Robinson Dike, on the east flank of the dome near the Fort Payne-New Albany contact, can be recognized by an occurrence of micaceous residuum in an old prospect pit. Examination of the weathered material by binocular microscope and by oil immersion techniques revealed a mass of unidentified cryptocrystalline weathering products containing abundant light brown mica flakes up to 10 mm across, scattered apatite crystals up to 2 mm long, and minor fresh, brown hornblende as cleavage fragments up to 2 or 3 mm long. No feldspar or feldspathic rock fragments were detected. A few fragments of black shale and chert in the sample could have been contaminants from the overlying soil. Absent evidence of igneous rock fragments suggests that the Robinson Dike is not a breccia but probably an ultramafic dike. Other ultramafic dikes and sills in the Illinois-Kentucky fluorspar mining district contain minor to major amounts of pyroxene but no hornblende (Clegg and Bradbury 1956, Koenig 1956).

Table 3 Rock composition analyses (X-ray fluorescence analyses of major elements).

Sample type and no.	Element as oxide (%)									
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	P_2O_5	CO_2
Vent breccia										
17 (Hamp)	96.3	0.15	1.96	1.18	0.30	0.25	1.00	1.00	*	*
20 (Pankey)	95.6	0.10	1.61	1.74	0.33	0.38	1.00	1.00	*	*
Shatter breccia										
New Albany										
14	50.4	0.67	13.80	4.07	2.94	7.26	4.56	4.45	*	9.89
37	47.2	0.68	12.70	3.76	2.98	10.50	2.92	4.91	*	12.23
51	92.4	0.12	3.56	1.67	0.17	0.15	1.00	1.00	*	*
Fort Payne										
28	97.2	0.17	2.00	0.52	0.14	0.20	1.00	1.00	*	*
40	98.0	0.06	1.81	1.08	0.10	0.19	1.00	1.00	*	*
41	96.5	0.13	2.36	0.66	0.28	0.14	1.00	1.00	*	*
43	96.2	0.25	2.80	1.09	0.28	0.19	1.00	1.00	*	*
55	95.0	0.15	3.15	0.89	0.13	0.10	1.00	1.00	*	*
Carbonatitic breccia										
47 (sideritic)	21.0	2.20	6.55	38.90	0.14	3.60	0.94	1.61	2.18	19.54
5 (Grant)	26.1	2.15	5.22	8.70	9.03	20.20	1.54	2.12	1.28	24.41

* Not detected

GEOCHEMISTRY OF THE BRECCIAS

Rock Composition Analysis

Vent and shatter breccias Analyses of the vent and shatter breccias (table 3) confirm the intensity of the silicification process in these breccias, all exposed at the surface. The extent of silicification in the siliceous shale breccia (sample 51) is indicated by depletion of alumina when compared with the amount of alumina in calcareous shale breccias (samples 14 and 37). The amount of alumina in the calcareous shale breccias is nearly four times that in the siliceous shale breccia.

The X-ray fluorescence (XRF) analyses of the calcareous New Albany shale breccias also confirm petrographic observations. Normative calculations on carbon dioxide (CO_2), calcium oxide (CaO), magnesium oxide (MgO), and total iron (as Fe_2O_3) in the calcareous shale breccias, samples 14 and 37, confirm that the carbonate minerals present are calcite and ferroan dolomite and that additional iron is present as pyrite, as determined by X-ray diffraction. The amount of potassium oxide (K_2O) in the calcareous shale breccia is normal for the New Albany shale (Frost et al. 1985) and most other pre-Pennsylvanian shales in Illinois (White 1959). The sodium oxide (Na_2O) content, abnormally high for the New Albany in Illinois, is similar to that reported in samples from core 11IL near the Joiner Dike (Frost et al. 1985, p. 64). The additional sodium is probably present in albite introduced during the brecciation-mineralization process.

Carbonatitic breccias Analysis of two carbonatitic breccias, samples 5 and 47, again confirm the results of the petrographic studies. Both samples contain abundant CO_2, which is present as dolomite and calcite in the Grant Intrusive (sample 5) and largely as siderite in the weather-resistant dike on the south flank of Hicks Dome (sample 47). The high content of iron in sample 47 and the relatively low MgO and CaO reflect the dominance of siderite to other carbonate minerals. The appreciable amounts of phosphorus pentoxide (P_2O_5) represent up to 5% apatite, which in fact, accounts for most of the CaO in sample 47. The relatively high titanium oxide (TiO_2) suggests an affinity with alkaline igneous activity (Heinrich 1966, Erickson and Blade 1963). The content of alkali metals depends primarily on the amount and kinds of feldspathic rock fragments and, to a lesser extent the amount of secondary feldspars, in the matrix. Part of the K_2O, however, is contained in the relatively abundant biotite and light brown mica.

Trace Element Analyses

The trace element analyses in table 4 clearly reflect the minor barite-lead-zinc mineralization of the central-area breccias (samples 17, 20, and 24). Other scattered, relatively high values in the central-area breccias, such as the 710 ppm of zirconium (Zr) and 1,600 ppm of strontium (Sr) in sample 24, appear to indicate that other components were introduced during the brecciation-mineralization. The 1,900 ppm of cobalt (Co) in sample 17 is inexplicably high, even considering possible sources of sample contamination.

In the New Albany shale breccia, the relatively high trace amounts of beryllium (Be) in sample 14 and barium (Ba) in sample 37 reflect the bertrandite and barite min-

Table 4 Trace element compositions (ppm) (Emission spectrographic analyses).

Sample type and no.	Mn	Cr	Pb	Sn	Bi	Ba	Be	Mo	V	Cu	Ag	Zn	Zr	Co	Ni	Sr
Vent breccia																
17 (Hamp)	14	220	1530	*	*	6100	8	8	45	20	*	*	150	1900	*	440
20 (Pankey)	21	110	760	*	*	*	10	3	34	8	*	100	130	250	*	230
24 (Pankey)	27	120	3100	*	32	2500	2	3	18	9	6	1050	710	300	*	1600
Shatter breccia																
New Albany																
14	600	75	19	*	*	*	240	6	110	*	*	*	170	90	34	500
37	370	120	38	*	50	2270	13	29	140	50	*	*	290	140	70	*
51	520	50	33	*	*	*	11	5	28	19	*	*	80	140	*	300
Fort Payne																
9	70	60	30	18	28	100	5	3	21	3	*	720	570	275	35	270
10	60	80	80	5	28	100	14	110	415	160	3	570	840	130	150	380
16	200	130	290	50	*	*	14	80	80	350	1	670	*	110	20	*
28	26	42	70	27	*	100	2	3	150	8	*	400	290	300	*	290
30	21	40	60	19	40	110	2	15	50	32	*	*	*	130	*	*
40	50	15	10	*	26	*	2	*	3	6	540	50	180	*	*	*
41	32	150	10	5	28	100	2	3	39	3	*	500	180	380	*	430
43	26	170	*	*	*	*	6	*	60	5	*	100	110	430	*	210
53	70	180	42	14	3	*	9	4	21	16	*	210	60	60	*	*
55	14	260	39	22	*	*	6	3	3	9	*	330	110	240	*	*
Carbonatitic breccias																
46 (weathered)	>7000	300	10	*	*	*	50	190	400	190	*	4000	1200	430	2200	3000
47 (sideritic)	>7000	400	70	*	*	*	45	85	320	95	90	2000	2800	465	210	1200
5 (Grant)	2400	130	18	*	28	100	13	12	170	60	3	4500	290	120	60	1800

* Not detected

eralization in those breccia bodies. The relatively high amount of manganese (Mn), 370 to 600 ppm, in all three shale breccias may, in part, be attributable to an original component in the parent shale. Unaltered New Albany has Mn contents of about 300 ppm (Frost et al. 1985, table C).

The relatively high trace amounts of Zr and Sr (table 4) in the carbonatitic breccias appear to be characteristic of rocks in alkalic provinces, such as at Magnet Cove, Arkansas (Erickson and Blade 1963, p. 53, 60-61). In addition the high Mn content, an order of magnitude greater than that reported in the shale breccias, and that of vanadium (V), may be attributable to alkalic igneous affinity. The relatively high amounts of chromium (Cr), copper (Cu), cobalt (Co), and nickel (Ni), particularly in samples 46 and 47, probably reflect the mafic character of the breccias (Vinogradov 1962). The high Ni content in sample 46 may represent, at least in part, a secondary enrichment during weathering. The 0.2% Ni (table 3) in the deeply weathered, carbonatitic breccia on the south flank of the dome is several times greater than that found in previously analyzed igneous rocks of the district (Bradbury 1962). The Ni concentration appears to be of little economic interest due to the small size of the host dike, about 3 feet (0.9 m) wide, and the probability that the high value is due to secondary enrichment. The rather high Zn content in all three samples is probably due to minor sphalerite mineralization. The absence of reported Nb may be related to its rather high (.01%) limit of detection.

The Fort Payne breccias contain no outstandingly high values for trace elements, but a few anomalous, higher-than-average amounts are present. Samples 9 and 10 are from a breccia dike in the Fort Payne Formation. The dike is at one end of a 200-foot-wide zone (61-m) of closely spaced fractures along a creek-bed outcrop of westward-dipping strata. The strata extend from the basal beds of Fort Payne into the top of the underlying shale of the New Albany Group. In the New Albany portion of the zone, a mineralized interval contains fluorite veinlets in vertical fractures and a high level of radioactivity. Sample 9 contains relatively high amounts of Zn and Zr, and sample 10 shows high levels of Mo, V, Cu, Zn, and Zr, elements that may be enriched in many alkaline complexes (Heinrich 1966, p. 222-241). Sample 16 is from a small area of breccia boulders on the Fort Payne ridge on the southeast flank of the dome. Enrichment in Pb, Cu, and Zn suggest that the breccia contains minor sulfide mineralization.

Fluorine (as Fluoride) Analysis

Samples from siliceous breccias in the central area (table 5, samples 17, 22, and 24) have low fluoride values and

evidently contain very little fluorite, even though on field examination some fluorite was found associated with all the central area breccia bodies. This discrepancy suggests that the fluorite is locally concentrated in the breccia bodies rather than disseminated throughout. This mode of occurrence probably results from the introduction of fluorine-bearing solutions after brecciation.

One of the three analyzed New Albany shale shatter breccias (sample 14) had a high fluoride content, and came from a dike with visible fluorite mineralization. The dike from which sample 37 came contained coarse barite, but the sample was surprisingly low in fluoride. The moderately high (802 ppm) fluoride in the siliceous shale breccia (sample 51) may represent traces of fluorite (not detected by microscopic examination) in the microgranular quartz cement.

The elevated fluoride values in the carbonatitic breccias are within the range of values reported for alkalic rocks by Shawe (1976, p. 5). Most of the fluorine in these breccias is probably contained in apatite, with the balance in biotite and light brown mica. The somewhat elevated fluorine in samples 46 and 57 from residuum in deeply weathered dikes may be related to apatite and micas concentrated by weathering. Since fluorite was observed in veinlets in the sideritic breccia dike near the weathered dike of sample 46 and in the drill core intersection near the Joiner Dike, the amounts of fluoride listed in table 5 for samples 46 and 57 may reflect minor amounts of fluorite in the samples.

The Fort Payne breccias, with the exception of sample 10, are relatively low in fluorine. The geologic setting of sample 10 is described in the section on Spectrographic Analyses. Although no fluorite was observed in samples of the dike rock examined visually, the fluorine in sample 10 is presumably present as fluorite, probably occurring as scattered, paper-thin veinlets in fractures, as was observed elsewhere in the 200-foot-wide fracture zone. Other Fort Payne breccias with higher-than-average amounts of fluoride, particularly sample 50 (544 ppm), may contain a little fluorite.

Table 5 Fluoride analyses (ion-selective electrode [ppm]).

Sample type and no.	F^-
Vent breccia	
17 (Hamp)	416
20 (Pankey)	*
24 (Pankey)	188
Shatter breccia	
New Albany	
14	4428
37	250
51	802
Fort Payne	
9	*
10	1728
16	328
28	*
40	*
41	*
43	*
53	408
55	*
Carbonatitic breccias	
46 (weathered)	3782
47 (sideritic)	2498
5 (Grant)	1674

* Not detected.

ORIGIN OF THE BRECCIAS

We interpret shatter, vent, and carbonatitic breccias to be related to explosive activity and the accompanying intrusion of alkaline igneous magma(s) at depth. The three breccia types, however, are sufficiently different in composition and physical character to warrant separate discussion of their origin.

Shatter Breccias

Because the shatter breccias at Hicks Dome lack vertical displacement of fragments and dike-like geometry, they appear to be similar to bodies associated with the breccia pipes in the Cordillera of North and South America and other parts of the world. Gates (1959) described the in-place breccias in the Shoshone Range, Nevada, and suggested that rock-bursting, such as is observed in manmade openings, was an important method of formation. Gilmour (1977) referred to this type of breccia as "fracture or shatter pipes." Bussel and McCourt (1977) in discussing similar breccia bodies ("burst breccias") associated with the Iglesia Irca intrusion in Peru, proposed an "origin by explosive brecciation with little or no transport at the present level." The same authors suggested further that such in-place brecciation was "the result of extremely rapid dilation of a fracture which results in the fragmentation, collapse, and comminution of the walls of the fracture." Such a mechanism is compatible with the characteristics of the shatter breccias at Hicks Dome and may explain their formation.

The partial rounding of clasts in some samples suggests movement of the shattered rock beyond a simple bursting into open fractures. Such movement was most likely imparted by a fluid that entrained and transported the finer rock particles sufficiently to cause a rounding of sharp corners on the larger fragments. Similar fluid transport forced finely particulate breccia into other cracks in the host rock, forming the irregular networks of narrow breccia veins observed in a few exposures. The limitation of clast lithologies, however, to the lithology

of the immediate host rock belies any significant vertical displacement comparable to that observed in the vent breccias and suggests that rock bursting was the dominant mechanism for formation of the shatter breccias.

Vent Breccias

The two vent breccias are composed of rock fragments from the host sedimentary strata. Vertical transport of fragments appears to have been as great as 1000 feet (300 m) in the Hamp well breccia (Brown et al. 1954, p. 893). The intense silicification of the fragments in the Pankey Breccia made identification of the original lithologies difficult. No fragments were observed that could not have come from the Devonian Grand Tower Limestone or the underlying Clear Creek Chert. As the country rock in the Pankey area is probably Grand Tower, maximum vertical displacement of Clear Creek fragments would be approximately 500 feet (150 m) (tables 1 and 2). The minimum displacement of Clear Creek fragments may be the depth to the top of the Clear Creek Chert at the Pankey site; this distance is unknown, but 50 to 100 feet is a reasonable approximation. Vertical transport of the breccia fragments was probably due to explosively released gases. The lack of reaction rims on the entrained fragments indicates (1) the gas was not reactive, (2) insufficient time for the reaction to take place, or (3) clasts that had earlier reaction rims were silicified along with the matrix and the rims thus obliterated.

Carbonatitic Breccias

The carbonatitic breccias contain rock and mineral fragments of igneous origin in a carbonate, or presumed former carbonate matrix. One carbonatitic breccia, the Grant Intrusive, also contains large hornblende and biotite crystals and crystal fragments and lapilli. Fragments of sedimentary rock also are abundant and become more abundant towards the margins of the only dike whose complete cross section was observable. Many of the sedimentary rock fragments have reaction rims. The origin of the carbonate matrix remains unclear, but the presence of uniformly thick reaction rims surrounding rock fragments indicates that reaction, pressumably with the gas or fluid that deposited matrix carbonate, occurred very early in the rock's history and suggests a magmatic origin. By contrast, many of the ultramafic dikes in the fluorspar district are extensively replaced by secondary carbonate (Clegg and Bradbury 1956, Koenig 1956), but sedimentary rock fragments in contact with carbonate in those dikes do not have reaction rims.

The igneous fragments, particularly the lapilli, and the displacement of sedimentary rock fragments are indicative of an explosive volcanic origin. Transport was probably by fluidization with the entraining agent, a CO_2-rich gas, emanating from a solidifying alkaline magma.

Evidence from Cementation and Mineralization

Secondary quartz or calcite serves as the cementing material in the vent and shatter breccias. Deposition of the secondary minerals followed breccia formation and was evidently genetically associated with brecciation. The existence of separate and distinct bodies of calcareous and siliceous breccias and the change within individual bodies from calcareous to siliceous cement (or vice versa) with repeated episodes of brecciation suggest that each episode was associated with a distinct fluid source.

Fluorite-sulfide-barite mineralization, if present, generally fills openings in the breccia cement, as veinlets and vug fillings, and is clearly subsequent to the primary brecciation in all but the calcareous shale shatter breccias. The mineralization, although closely related to the brecciation, is in some instances fractured and veined by later calcite or quartz.

The extensive silicification observed in most of the breccias, while seemingly at odds with alkaline igneous activity, is, nevertheless, characteristic of many carbonatitic complexes. Heinrich (1966, p. 199-203) points out the abundant silicification of carbonatites and associated rocks at Mountain Pass (California), Powderhorn (Colorado), and many other localities, as well as the late-stage mineralization characterized by veins containing fine-grained quartz, along with fluorite, barite, sulfides, or apatite. Late-stage, thorium-bearing veins, associated with a number of carbonatitic complexes, also contain quartz as a major constituent (Olson et al. 1954, Staatz 1972, Olson et al. 1977).

Age of Brecciation

The age of explosive igneous activity at Hicks Dome appears to be early Permian (270 Ma) on the basis of averaging K-Ar dating of biotite (258+13 my) and hornblende (281 + 14 my) from the Grant Intrusive (Zartman et al. 1967). T. S. Hayes (USGS, personal communication, 1991) emphasized that the K-Ar dates are based on "closure-temperature." They are cooling dates that are set as the temperature moves through the minerals' blocking temperature (about 420° to 500°C for hornblende and 220° to 250°C for biotite) and therefore, indicate a minimum age for the intrusive. The biotite and hornblende are clearly xenocrysts and, as such, existed as crystals before their transport and emplacement as breccia components. The rims (lapilli), interpreted as crystallized melt around individual hornblende and biotite crystals, suggest that the hornblende and biotite crystals existed within a magma prior to entrainment in the breccia column. Early Permian dates on biotite from mica peridotites at two localities elsewhere in the Fluorspar District (Zartman et al. 1967) emphasize that igneous intrusion was taking place throughout the district at this time.

An alternative hypothesis for the age of brecciation can be argued based on recognition of the unique geochemical signature of Hicks Dome mineralization and on an assumption that uplift, brecciation, and the exotic mineralization at Hicks Dome are separated in time from the widespread introduction of basic igneous dikes and carbonatitic breccias. The major explosive activity at

Hicks Dome could have been related to reactivation of the New Madrid Rift Complex in the Mesozoic (Early Jurassic-Late Cretaceous). This view is supported by the lead-alpha date of 90 to 100 Ma on the mineral brockite (calcium, thorium phosphate) at Hicks Dome (Heyl and Brock 1961). Ruiz et al. (1988) point out, however, that lead-alpha age determinations are "fraught with uncertainty" and raise the possibility that the 90 to 100 Ma date could conceivably be as much as 100 Ma too young. They have compared the isotopic evolution of strontium in biotites from alkalic rocks of 290 Ma (dated by Zartman et al. 1967) to observed strontium isotopic composition in fluorite from the Cave-in-Rock district. The strontium isotope data are interpreted to indicate that 200 Ma ago (Jurassic-Triassic), the biotites in the dikes attained strontium isotope ratios similar to the isotopic composition of fluorite from the Cave-in-Rock district. Ruiz et al. (1988) suggest that the similarity was achieved by incongruent dissolution of the older biotites by heated solutions, the origin of which they speculatively relate to postdike igneous activity at Hicks Dome. Such activity might occur in association with the crustal extension and rift reactivation accompanying the breakup of Pangea. A Mesozoic date would correspond in time to the intrusion of alkalic igneous rocks along the axis of the Reelfoot Rift in western Tennessee and southwest Missouri, and adjacent to the Rift in central Arkansas (Moody 1949, Kidwell 1951).

Whatever the timing of post-Appalachian crustal deformation, it is likely that the Hicks Dome explosive events, with their unique geochemical signature—fluorine, lead, zinc, barium, thorium, beryllium, titanium and rare earth elements—probably were related to reactivation of the New Madrid Rift Complex and to deep-seated igneous activity, with a contribution of material from the mantle.

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